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FIRESTORM ANALYSIS  
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T. E. Lommasson  
J. A. Keller  
R. G. Kirkpatrick

Prepared on Contract No. 13-248

for

Division of Fire Research  
U. S. Forest Service  
Department of Agriculture  
Washington, D. C.

This Project Sponsored By  
**The Advanced Research Projects Agency**  
**Department of Defense**

February 1, 1967

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**Dikewood**  
CORPORATION

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## CONTENTS

<u>Section</u>	<u>Page</u>
List of Appendices . . . . .	ii
List of Illustrations . . . . .	iii
 1.0 INTRODUCTION . . . . .	 1
1.1 Objectives . . . . .	1
1.2 Background . . . . .	1
1.3 Method of Calculation . . . . .	2
1.4 Limitations . . . . .	3
 2.0 RESULTS . . . . .	 5
2.1 Radial Inrush Wind Velocity . . . . .	5
2.2 Sensitivity Analysis . . . . .	5
2.3 Accelerated Spread Study . . . . .	6
 References . . . . .	 9



## LIST OF APPENDICES

<u>Appendix</u>	<u>Title</u>
IA	Rationale for Computation of Radial Inrush Wind Velocity
IB	Derivation of the Basic Equation
IC	Development of Spread Rate Relationships
ID	Derivation of Coalescence Equations
II	Rationale for Sensitivity Analysis
III	Computer Program for Inrush Wind and Sensitivity Calculations
IV	Radial Inrush Wind Velocity Curves
V	Sensitivity Curves
VI	Accelerated Spread Study
VII	Accelerated Spread Program
VIII	Accelerated Spread Curves

## LIST OF ILLUSTRATIONS

<u>Fig. No.</u>		<u>Page</u>
RADIAL INDRAFT WIND VELOCITY CURVES		
<u>Case 1</u> , Constant Area Increase, $K = 5.0 \text{ ft}^2/\text{sec}$		
Fuel Loading = 5 tons/acre		
IV- 1	Area = 1 square mile . . . . .	IV- 2
IV- 2	Area = 5 square miles . . . . .	IV- 3
IV- 3	Area = 10 square miles . . . . .	IV- 4
IV- 4	Area = 15 square miles . . . . .	IV- 5
IV- 5	Area = 25 square miles . . . . .	IV- 6
Fuel Loading = 15 tons/acre		
IV- 6	Area = 1 square mile . . . . .	IV- 7
IV- 7	Area = 5 square miles . . . . .	IV- 8
IV- 8	Area = 10 square miles . . . . .	IV- 9
IV- 9	Area = 15 square miles . . . . .	IV-10
IV-10	Area = 25 square miles . . . . .	IV-11
Fuel Loading = 30 tons/acre		
IV-11	Area = 1 square mile . . . . .	IV-12
IV-12	Area = 5 square miles . . . . .	IV-13
IV-13	Area = 10 square miles . . . . .	IV-14
IV-14	Area = 15 square miles . . . . .	IV-15
IV-15	Area = 25 square miles . . . . .	IV-16
<u>Case 2a</u> , Constant Perimeter Increase, $L = 0.1 \text{ ft}/\text{sec}$		
Fuel Loading = 5 tons/acre		
IV-16	Area = 1 square mile . . . . .	IV-17
IV-17	Area = 5 square miles . . . . .	IV-18
IV-18	Area = 10 square miles . . . . .	IV-19
IV-19	Area = 15 square miles . . . . .	IV-20
IV-20	Area = 25 square miles . . . . .	IV-21
Fuel Loading = 15 tons/acre		
IV-21	Area = 1 square mile . . . . .	IV-22
IV-22	Area = 5 square miles . . . . .	IV-23
IV-23	Area = 10 square miles . . . . .	IV-24
IV-24	Area = 15 square miles . . . . .	IV-25
IV-25	Area = 25 square miles . . . . .	IV-26

# LIST OF ILLUSTRATIONS (Continued)

<u>Fig. No.</u>		<u>Page</u>
	Fuel Loading = 30 tons/acre	
IV-26	Area = 1 square mile.....	IV-27
IV-27	Area = 5 square miles.....	IV-28
IV-28	Area = 10 square miles.....	IV-29
IV-29	Area = 15 square miles.....	IV-30
IV-30	Area = 25 square miles.....	IV-31
	Case 2b, Constant Radial Increase, M = 0.01 ft/sec	
	Fuel Loading = 5 tons/acre	
IV-31	Area = 1 square mile.....	IV-32
IV-32	Area = 5 square miles.....	IV-33
IV-33	Area = 10 square miles.....	IV-34
IV-34	Area = 15 square miles.....	IV-35
IV-35	Area = 25 square miles.....	IV-36
	Fuel Loading = 15 tons/acre	
IV-36	Area = 1 square mile.....	IV-37
IV-37	Area = 5 square miles.....	IV-38
IV-38	Area = 10 square miles.....	IV-39
IV-39	Area = 15 square miles.....	IV-40
IV-40	Area = 25 square miles.....	IV-41
	Fuel Loading = 30 tons/acre	
IV-41	Area = 1 square mile.....	IV-42
IV-42	Area = 5 square miles.....	IV-43
IV-43	Area = 10 square miles.....	IV-44
IV-44	Area = 15 square miles.....	IV-45
IV-45	Area = 25 square miles.....	IV-46

## SENSITIVITY CURVES

V-1	$\partial v_w / \partial n$ vs. n .....	V-2
V-2	$\partial v_w / \partial A$ vs. A .....	V-3
V-3	$\partial v_w / \partial FL$ vs. FL .....	V-4

LIST OF ILLUSTRATIONS  
(Continued)

<u>Fig. No.</u>		<u>Page</u>
V-4	$\partial v_w / \partial E_{\text{fuel}}$ vs. $E_{\text{fuel}}$ . . . . .	V-5
V-5	$\partial v_w / \partial E_{\text{frac, viol}}$ vs. $E_{\text{frac, viol}}$ . . . . .	V-6
V-6	$\partial v_w / \partial E_{\text{frac, resid}}$ vs. $E_{\text{frac, resid}}$ . . . . .	V-7
V-7	$\partial v_w / \partial r$ vs. $M$ . . . . .	V-8
VI-1	ACCELERATED SPREAD PARAMETER DEFINITIONS. .	VI-1

ACCELERATED SPREAD CURVES

VIII-1	Radial Spread Rate vs. Time for Initial Mode 1 . . . . .	VIII-2
VIII-2	Radial Spread Rate vs. Fire Radius for Initial Mode 1 . .	VIII-3
VIII-3	Radial Spread Rate vs. Time for Initial Mode 2 . . . . .	VIII-4
VIII-4	Radial Spread Rate vs. Fire Radius for Initial Mode 2 . .	VIII-5
VIII-5	Radial Spread Rate vs. Time for Initial Mode 3 . . . . .	VIII-6
VIII-6	Radial Spread Rate vs. Fire Radius for Initial Mode 3 . .	VIII-7
VIII-7	Radial Spread Rate vs. Time for Initial Mode 4 . . . . .	VIII-8
VIII-8	Radial Spread Rate vs. Fire Radius for Initial Mode 4 . .	VIII-9

## FIRESTORM ANALYSIS

### 1.0 INTRODUCTION

#### 1.1 Objectives

The following general objectives were specified for this study:

- a) Compute the radial inrush wind ( $v_w$ ) associated with a mass fire as a function of time and various fuel bed parameters,
- b) Investigate the sensitivity of  $v_w$  to variations in certain of the fuel bed parameters, and
- c) Conduct an analytical study of the case in which fire spread is accelerated by wind and/or flame interaction until coalescence.

#### 1.2 Background

The basic point of departure for this research was Ref. 1, in which a hypothesis was developed relating radial inrush wind velocity at the edge of a potential firestorm area to the energy release rate of fires within the area and to the size of the area itself. The value of the constant in the equation relating these parameters was determined by "fitting" an equation derived from physical considerations to estimated "worst case" conditions during the Hamburg firestorm. One degree of freedom in the "constant" term allowed this fit to be made.

In Appendix IB, the equation of Ref. 1 is expanded to express the energy release rate of the fires in terms of the following parameters:

$n$	the number of initial fires,
$FL$	the fuel loading,
$E_{fuel}$	the energy content of the fuel,
$A_{SV}$	the area of a single fire which is in the violent burning stage* at a given time,
$A_{SR}$	the area of a single fire which is in the residual burning stage* at a given time,
$E_{frac, viol}$	the fraction of $E_{fuel}$ released during the violent burning stage*,
$E_{frac, resid}$	the fraction of $E_{fuel}$ released during the residual burning stage*,
$\Delta t_V$	the duration of the violent burning period, * and
$\Delta t_R$	the duration of the residual burning period*.

In Appendices IA and IC, equations are derived which, for certain assumptions, represent  $A_{SV}$  and  $A_{SR}$  as a function of time, spread rate, and other parameters for three different spread conditions.

### 1.3 Method of Calculation

A computer program to calculate  $v_w$  was written based upon Eq. (IA-1) and Tables IA-I and IA-II. The input values used are listed in Section IA. 4. The results of these calculations are presented graphically in

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\* The definitions of "violent" and "residual" burning regimes are based upon Ref. 2.

Appendix IV. A second part of the program calculates the partial derivative of  $v_w$  with respect to seven selected parameters based upon the rationale of Appendix II and using the inputs listed in Table II-I. The results of this series of calculations is presented in Appendix V. A listing of this program, its input requirements, and a sample output page from each part are contained in Appendix III.

The accelerated spread study considers that radial spread is accelerated by interaction effects (after adjacent fires reach a certain minimum separation distance). Four initial spread modes are investigated: a constant rate of radial increase, a constant rate of area increase, and two logarithmic rates of radial spread.\*

The computer program listed in Appendix VII calculates spread rate, fire radius, and distance to the point at which flame fronts merge as a function of time for each initial spread mode. This program is based upon the equations of Appendix VI. Appendix VIII contains eight graphs showing radial spread rate as a function of time and of fire radius for each of the initial spread modes, with the point at which acceleration begins indicated on each curve.

#### 1.4 Limitations

Inherent in the rationales and the results of this study are, of course, the approximations and assumptions made in deriving the heuristic model

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\* Provided by Mr. C. C. Chandler, Division of Fire Research, U. S. Forest Service, Washington, D. C.

from Ref. 1 and the modifications to it described in Section 1.2. In particular, the "worst case" conditions in Hamburg, from which the value of the constant was obtained, corresponds to 100% simultaneous involvement of all structures in an urban area during the violent burning period of the initial fires. This study considers a continuous wildland fuel bed with somewhat different burning characteristics. The degree of correspondence between these two cases is not, as yet, firmly established.

All of the  $v_w$  computations are made using average values for the rate of energy release term, as reflected by the parameters listed on pages IA-1 and IA-2.

Also, the type and rate of fire spread which occur in a fuel bed of the sort considered here will probably require considerable further investigation before the functional dependencies and appropriate parameter values are clearly defined. The preliminary work on accelerated spread in this study is one course of investigation that may yield a better understanding of these relationships.

The spread rate relations assumed are approximations, and in the real world probably represent rough average values as they develop as a function of time.

This entire study may be viewed as a project that has generated a number of rough hypotheses which may now be tested and assessed as to validity and utility.



## 2.0 RESULTS

### 2.1 Radial Inrush Wind Velocity Curves

The 45 families of curves in Appendix IV represent  $v_w$  as a function of  $n$  for ten values of time after ignition. A family of curves was constructed for each combination of values of 3 spread cases, 3 fuel loadings, and 5 area sizes. Each family is bounded above by the coalescence locus, as discussed in Appendix ID.

In general, an increase in the number of initial ignitions decreases the time at which the maximum value of  $v_w$  ( $\hat{v}_w$ ) occurs, as would be expected. For Case 1 (constant area increase),  $\hat{v}_w$  (as described by the coalescence locus) increases considerably as a function of  $n$ . On the other hand, for Case 2 (constant rate of perimeter or radial increase), the coalescence locus is much "flatter"; i. e.,  $\hat{v}_w$  is fairly constant with respect to  $n$ . This simply means that, as  $n$  increases, the time to coalescence is less for spread Case 1 than for spread Case 2, all other factors being equivalent. Also, for the values of the spread constants considered in this analysis,  $\hat{v}_w$  appears to occur at a much earlier time for Case 1 than for Case 2, which is intuitively expected.

### 2.2 Sensitivity Analysis

Appendix V contains seven families of curves which represent  $\frac{\partial v_w}{\partial \mu_i}$  at ten times after ignition as a function of  $\mu_i$  with the other parameters  $\mu_j$  ( $j \neq i$ ) held at their "representative values." These curves are drawn

from the output of Part II of the computer program listed in Appendix III.

This part of the program and its inputs are based upon the rationale described in Appendix II.

The partial derivative  $\frac{\partial v_w}{\partial \mu_i}$  indicates the rate of change of  $v_w$  with respect to  $\mu_i$ . The sign of  $\frac{\partial v_w}{\partial \mu_i}$  indicates the direction of change, e. g., if  $\frac{\partial v_w}{\partial \mu_i} > 0$ , an increase in the value of  $\mu_i$  will result in an increase in the value of  $v_w$ . Conversely, if  $\frac{\partial v_w}{\partial \mu_i} < 0$ , then an increase in  $\mu_i$  will yield a decrease in  $v_w$ . The magnitude  $\left| \frac{\partial v_w}{\partial \mu_i} \right|$  serves as an index of the rate of change for various points on the family of curves associated with a particular  $\mu_i$ . Table 2.2-I lists the sign of  $\frac{\partial v_w}{\partial \mu_i}$  and the behavior of  $\left| \frac{\partial v_w}{\partial \mu_i} \right|$  for the seven parameters considered.

### 2.3 Accelerated Spread Study

Appendix VI considers the case in which radial spread rate is accelerated by interaction effects when adjacent fires are sufficiently close. This case is investigated for four initial spread modes; two logarithmic rates of radial increase,\* the constant rate of radial spread ( $M = 0.01$  ft/sec) used for Case 2b of the  $v_w$  calculations, and the constant rate of area spread ( $K_1 = 5.0$  ft<sup>2</sup>/sec) used for Case 1 of the  $v_w$  calculations.

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\* Provided by Mr. C. C. Chandler, Division of Fire Research, U. S. Forest Service, Washington, D. C.

from the output of Part II of the computer program listed in Appendix III. This part of the program and its inputs are based upon the rationale described in Appendix II.

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Appendix VI considers the case in which radial spread rate is accelerated by interaction effects when adjacent fires are sufficiently close. This case is investigated for four initial spread modes; two logarithmic rates of radial increase, \* the constant rate of radial spread ( $M = 0.01$  ft/sec) used for Case 2b of the  $v_w$  calculations, and the constant rate of area spread ( $K_1 = 5.0$  ft<sup>2</sup>/sec) used for Case 1 of the  $v_w$  calculations.

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TABLE 2.2-I

Sensitivity Summary

Parameter	Sign of $\frac{\partial v}{\partial \mu_i}$	Change in $\left  \frac{\partial v}{\partial \mu_i} \right $ with increasing $\mu$ 's for a fixed time.	Change in $\left  \frac{\partial v}{\partial \mu_i} \right $ with increasing time for a fixed value of $\mu_i$ .
$\mu_1 = n$	+	decreasing	increasing
$\mu_2 = A$	-	decreasing	increasing
$\mu_3 = FL$	+	decreasing	increasing
$\mu_4 = EF$	+	decreasing	increasing
$\mu_5 = E_{frac, viol}$	+	decreasing	increasing for $t \leq 32$ min. decreasing for $t > 32$ min.
$\mu_6 = E_{frac, resid}$	-	increasing	increasing for $t \leq 32$ min. decreasing for $t > 32$ min.
$\mu_7 = r$ ( $r = 2\pi M^2 t$ )	+	decreasing	decreasing

Equations are developed for radial spread rate, fire radius, and distance to merging as a function of time for each initial spread mode. The computer program listed in Appendix VII is based upon these equations.

The eight graphs in Appendix VIII represent radial spread rate as a function of time and of fire radius for each initial spread mode.

## REFERENCES

1. Lommasson, T. E., Preliminary Investigation of Firestorm Start-Criteria, The Dikewood Corporation DC-TN-1050-1, Contract OCD-PS-65-53, Albuquerque, New Mexico, June 15, 1965.
2. Chandler, C. C., Storey, T. G., and Tangren, C. D., Prediction of Fire Spread Following Nuclear Explosions, U. S. Forest Service Research Paper PSW-5, Contract OCD-OS-62-131, Berkeley, California, 1963.

## APPENDIX IA

### RATIONALE FOR COMPUTATION OF RADIAL INRUSH WIND VELOCITY

#### IA.1 Basic Equation and Parameter Definitions

The basic equation\* is

$$v_w = \left( \frac{88}{1000} \right) \left( \frac{50}{1089} \right)^{1/3} \cdot \frac{[(n)(FL)(E_{fuel})]^{1/3}}{A^{1/6}} \cdot \left[ \frac{A_{SV}(r,t,\Delta t_V) \cdot E_{frac,viol}}{\Delta t_V} + \frac{A_{SR}(r,t,\Delta t_V,\Delta t_R) \cdot E_{frac,resid}}{\Delta t_R} \right]^{1/3} \quad (IA.1)$$

Where

$v_w$	is the radial inrush wind velocity at the periphery of a circular area $A$ within which fires are burning, in miles per hour
$n$	is the number of initial fires. [ $n = n_d \cdot (A)$ , where $n_d$ is the number of initial fires per square mile ]
$FL$	is the fuel loading, in tons per acre
$E_{fuel}$	is the caloric content of the fuel in Btu/lb
$A$	is the total area within which fires are started, in square miles
$A_{SV}$	is the area which is in the violent burning regime at time $t$ , in square feet

---

\* This equation is based on work done in Ref. 1. A derivation of the form used in this study from those in Ref. 1 is given in Appendix IB.

$r$  is the spread rate; if  $A_S$  denotes the total area, in square feet, over which the fire has spread at time  $t$ ,

$$r = \frac{dA_S}{dt} \quad (\text{IA. 2})$$

$t$  is the time after ignition, in seconds

$\Delta t_V$  is the duration of the violent burning period, in seconds

$E_{\text{frac, viol}}$  is the fraction of the total available energy of the fuel which is released during the violent burning period

$A_{SR}$  is the area which is in the residual burning regime at time  $t$ , in square feet

$\Delta t_R$  is the duration of the residual burning period, in seconds

$E_{\text{frac, resid}}$  is the fraction of the total available energy of the fuel which is released during the residual burning regime

## IA. 2 Assumptions

- A. All fires have negligible initial areas; i. e., they are effectively "point fires".
- B. Fire spread starts immediately after initiation of any given "point fire", and each fire spreads in the same manner at the same rate symmetrically around the "point fire" until coalescence.
- C. All fires are started simultaneously from a uniform distribution of ignitions and burn in identical fuel beds.



D. Three rates of area spread with time will be considered:

- 1)  $\frac{dA_S}{dt} = r_1 = K_1$ , which represents a constant rate of area growth,
- 2)  $\frac{dA_S}{dt} = r_2 = Bt$ , which represents a constant rate of perimeter increase,
- 3)  $\frac{dA_S}{dt} = r_3 = Ct$ , which represents a constant rate of radial spread.

The expressions for B and C are derived in Appendix IC.

### IA.3 Procedure

At any time  $t$ , the area into which a given fire has spread,  $A_S$ , is composed, ideally, of three regions:

- 1) The violently burning part,  $A_{SV}$ ,
- 2) The residually burning part,  $A_{SR}$ , and
- 3) The burned-out portion,  $A_{SBO}$ , so that

$$A_S(t) = A_{SV}(t) + A_{SR}(t) + A_{SBO}(t) \quad (\text{IA. 3})$$

From the definitions, it is apparent that

$$A_{SV}(t) = A_S(t) - A_S(t - \Delta t_V)$$

$$A_{SR}(t) = A_S(t - \Delta t_V) - A_S[t - (\Delta t_V + \Delta t_R)]$$

$$A_{SBO}(t) = A_S[t - (\Delta t_V + \Delta t_R)] \quad (\text{IA. 4})$$

Taking  $r(t)$  as the spread rate, one may write the following relations:

$$A_{SBO} = \begin{cases} 0 & \text{if } t \leq \Delta t_V + \Delta t_R \\ \int_{\Delta t_V + \Delta t_R}^t r[t - (\Delta t_V + \Delta t_R)] dt & \text{for } t > \Delta t_V + \Delta t_R \end{cases} \quad (\text{IA. 5})$$

$$A_{SR} = \begin{cases} 0 & \text{if } t \leq \Delta t_V \\ \int_{\Delta t_V}^t r(t - \Delta t_V) dt - A_{SBO} & \text{for } t > \Delta t_V \end{cases} \quad (\text{IA. 6})$$

and

$$A_{SV} = \int_0^t r(t) dt - A_{SR} - A_{SBO} \quad (\text{IA. 7})$$

These expressions have been evaluated and the results are given in Tables IA-I and IA-II, which present formulae for  $A_{SV}$ ,  $A_{SR}$ , and  $A_{SBO}$  as a function of time for the two basic spread modes given in paragraph IA. 2D above.

Case 1. Constant area increase.

$$r = \frac{dA_S}{dt} = K_1 \text{ ft}^2 / \text{sec} \quad (\text{IA. 8})$$

Table IA - I

$\begin{matrix} t \\ A_S \end{matrix}$	$0 \leq t \leq \Delta t_V$	$\Delta t_V < t \leq \Delta t_V + \Delta t_R$	$t > \Delta t_V + \Delta t_R$
$A_{SV}$	$rt$	$r \cdot \Delta t_V$	$r \cdot \Delta t_V$
$A_{SR}$	-0-	$r \cdot (t - \Delta t_V)$	$r \cdot \Delta t_R$
$A_{SBO}$	-0-	-0-	$r \cdot [t - (\Delta t_V + \Delta t_R)]$

In this case

$$n_c = \frac{A}{K_1 t} \times (5280)^2 \quad (\text{IA. 9})$$

where  $n_c$  is the number of initial fires necessary to achieve coalescence in area  $A$  by time  $t$ . \*

$$\text{Case 2.} \quad r = \frac{dA_S}{dt} = K_2 t \quad (\text{IA. 10})$$

(2a)  $K_2 = B$  (constant rate of perimeter increase)  $B = L^2 / (2\pi)$   
 where  $L$  is rate of change of perimeter, in feet per second. \*\*

(2b)  $K_2 = C$  (constant rate of radial increase)  $C = 2\pi M^2$   
 where  $M$  is rate of change of radius, in feet per second. \*\*

\* The derivation of the coalescence relations is given in Appendix ID.

\*\* The derivation of these relationships is given in Appendix IC.

Table IA - II

$\begin{matrix} t \\ A_S \end{matrix}$	$0 \leq t \leq \Delta t_V$	$\Delta t_V < t \leq \Delta t_V + \Delta t_R$	$t > \Delta t_V + \Delta t_R$
$A_{SV}$	$\frac{rt}{2}$	$\frac{r}{2} \cdot \left[ 2\Delta t_V - \frac{(\Delta t_V)^2}{t} \right]$	$\frac{r}{2} \cdot \left[ 2\Delta t_V - \frac{(\Delta t_V)^2}{t} \right]$
$A_{SR}$	-0-	$\frac{r}{2} \cdot \left[ t - 2\Delta t_V + \frac{(\Delta t_V)^2}{t} \right]$	$\frac{r}{2} \cdot \left[ 2\Delta t_R - \frac{2\Delta t_V \Delta t_R}{t} - \frac{(\Delta t_R)^2}{t} \right]$
$A_{SBO}$	-0-	-0-	$\frac{r}{2} \cdot \left[ t - 2(\Delta t_V + \Delta t_R) + \frac{(\Delta t_V + \Delta t_R)^2}{t} \right]$

and

$$n_c = \frac{2A}{K_2 t^2} \times (5280)^2 \quad (\text{IA. 11})$$

#### IA. 4 Input Parameter Values

Calculations of  $v_w$  and  $n_c$  have been made for each case, using each combination of the parameter values:

$$n_d = 2000, 3000, 4000, 4500, 5000, 6000, 7000, 10,000$$

$$A = 1.0, 5.0, 10.0, 15.0, 25.0 \text{ mi}^2$$

$$FL = 5, 15.0, 30.0 \text{ tons/acre}$$

$$E_{\text{fuel}} = 7000 \text{ Btu/lb}$$

$$\Delta t_V = 360 \text{ sec}$$

$$\begin{aligned}
 \Delta t_R &= 4200 \text{ sec} \\
 K_1 &= 5.0 \text{ ft}^2/\text{sec} \\
 M &= .01 \text{ ft/sec} \\
 L &= .1 \text{ ft/sec} \\
 E_{\text{frac, viol}} &= 0.4 \\
 E_{\text{frac, resid}} &= 0.6 \\
 t &= 2, 4, 6, 8, 16, 24, 32, 48, 64, 80 \text{ minutes}
 \end{aligned}$$

Note that the total number of fires burning in a given area is represented by  $n = n_d \cdot A$ .

#### IA. 5 Method of Calculation

A computer program was written based upon the above equations. Using the inputs listed above, it calculates  $v_w$  as a function of time and  $n$  for each combination of the other parameters. A listing of this program, its input format requirements, and a sample output page is included in Appendix III. The output is grouped so that:

- 1) All pages pertaining to a given spread rate are together.
- 2) Within a given case, all pages with a specific FL are together.
- 3) Each page of the output has all the points for a specific area size, given the case and FL.

The results of these calculations are presented graphically in Appendix IV.

# APPENDIX IB DERIVATION OF THE BASIC EQUATION

Equation (29) of Ref. 1 gives

$$v_w = \frac{(88 \times 10^{-3}) \left[ \sum_{i=1}^n \frac{dE_{T(i)}}{dt} \right]^{1/3}}{\sqrt[6]{A}} \quad (\text{IB. 1})$$

where  $v_w$  is the radial inrush wind velocity at the periphery of area A, in miles per hour, n is the number of initial fires started in an area A, and  $\frac{dE_{T(i)}}{dt}$  is the energy release rate for a single fire, in Btu/sec at time t.

Assuming identical simultaneously ignited fires in a continuous fuel bed with uniform characteristics, the total amount of energy released during the violent burning period is given by the product of:

- 1) the total number of fires,
- 2) the fuel loading ( $\text{lbs/ft}^2$ ),
- 3) the caloric content of the available fuel (Btu/lb),
- 4) the area ( $\text{ft}^2$ ) which is burning violently at the time in question, and
- 5) the fraction of the total energy of the fuel which is released during the violent burning period.

The average energy release rate during the violent burning regime is the total energy released during that time divided by the length of the violent burning period, in seconds. Symbolically,

$$\left[ \sum_{i=1}^n \frac{dE_{T(i)}}{dt} \right]_{\text{viol}} = \frac{(n)(FL)(E_{\text{fuel}})(A_{SV})(E_{\text{frac, viol}})}{\Delta t_V} \quad (\text{IB. 2})$$

Similarly, the energy release rate during the residual burning period may be represented by

$$\left[ \sum_{i=1}^n \frac{dE_{T(i)}}{dt} \right]_{\text{resid}} = \frac{(n)(FL)(E_{\text{fuel}})(A_{SR})(E_{\text{frac, resid}})}{\Delta t_R} \quad (\text{IB. 3})$$

If fuel loading (FL) is expressed in tons per acre, the expressions on the right in Eqs. (IB. 2) and (IB. 3) must be multiplied by the conversion factor (50/1089).

The total energy release rate is the sum of the release rate for those portions of the fuel bed in the violent burning regime and for the portions in the residual regime, or

$$\left[ \sum_{i=1}^n \frac{dE_{T(i)}}{dt} \right]_{\text{total}} = \left[ \sum_{i=1}^n \frac{dE_{T(i)}}{dt} \right]_{\text{viol}} + \left[ \sum_{i=1}^n \frac{dE_{T(i)}}{dt} \right]_{\text{resid}} \quad (\text{IB. 4})$$

Substituting Eqs. (IB. 2), (IB. 3), and (IB. 4) into Eq. (IB. 1), using the conversion factor, and simplifying yields

$$v_w = \left( \frac{88}{1000} \right) \left( \frac{50}{1089} \right)^{1/3} \frac{[(n)(FL)(E_{\text{fuel}})]^{1/3}}{\sqrt[6]{A}} \left[ \frac{A_{SV} \cdot E_{\text{frac, viol}}}{\Delta t_V} + \frac{A_{SR} \cdot E_{\text{frac, resid}}}{\Delta t_R} \right]^{1/3} \quad (\text{IB. 5})$$

which is the desired result. In this expression  $A_{SV}$  is a complex function of  $r$ ,  $t$ , and  $\Delta t_V$ , and  $A_{SR}$  is a complex function of  $r$ ,  $t$ ,  $\Delta t_V$  and  $\Delta t_R$

## APPENDIX IC

### DEVELOPMENT OF SPREAD RATE RELATIONSHIPS

The expressions for B and C, as defined under assumption (D),  
Section IA. 2, may be derived as follows:

a) Let the perimeter of a fire be approximated by  $P = 2\pi r_c$ ,  
where  $r_c$  is the radius of the circular fire front and is a function of time.  
If the rate of perimeter growth is constant, then

$$\frac{dP}{dt} = L \quad , \quad (\text{IC. 1})$$

where L is the constant rate of perimeter increase in units of length per  
unit of time.

From Eq. (IC. 1),

$$P = Lt = 2\pi r_c \quad , \quad (\text{IC. 2})$$

and

$$r_c = \frac{Lt}{2\pi} \quad . \quad (\text{IC. 3})$$

Now,

$$A_S = \pi r_c^2 = \frac{L^2 t^2}{4\pi} \quad . \quad (\text{IC. 4})$$

Differentiation of Eq. (IC. 4) yields

$$\frac{dA_S}{dt} = \frac{L^2 t}{2\pi} = r_2 = Bt \quad . \quad (\text{IC. 5})$$



Solving for B yields

$$B = \frac{L^2}{2\pi} . \quad (\text{IC. 6})$$

b) Similarly, if  $r_c$  again represents the radius of a circular fire front and M represents a constant rate of radial spread in units of length per unit of time, one may write

$$\frac{dr_c}{dt} = M \quad (\text{IC. 7})$$

so that

$$r_c = Mt , \quad (\text{IC. 8})$$

and

$$A_S = \pi r_c^2 = \pi M^2 t^2 . \quad (\text{IC. 9})$$

Hence

$$\frac{dA_S}{dt} = 2\pi M^2 t = r_3 = Ct , \quad (\text{IC. 10})$$

and therefore

$$C = 2\pi M^2 . \quad (\text{IC. 11})$$

## APPENDIX ID

### DERIVATION OF COALESCENCE EQUATIONS

The  $v_w$  versus  $n$  curves are bounded by the "coalescence locus", which may be defined as the number of initial fires necessary to achieve coalescence\* by a specified time.

Assuming a uniform density of  $(n)$  ignitions, the area in square feet available to a single fire for spread before coalescence is

$$A_S = \frac{A \times (5280)^2}{n} \quad (\text{ID. 1})$$

Also,

$$A_S(t) = \int_0^t r(t) dt \quad (\text{ID. 2})$$

If  $r(t) = K_1$  (Case 1),

$$A_S(t) = K_1 t \quad (\text{ID. 3})$$

Equating (ID. 1) and (ID. 3) yields, for Case 1,

$$n_c = \frac{A \times (5280)^2}{K_1 t} \quad (\text{ID. 4})$$

---

\* At coalescence all of the individual fires have merged into a single large fire, and it is assumed that no regions within the area remain unburned.

where  $n_c$  represents the approximate number of initial fires required for coalescence by time  $t$ . The approximation results from geometric assumptions inherent in Eq. (ID. 4).

In Case 2,

$$r = K_2 t \quad , \quad (\text{ID. 5})$$

and Eq. (ID. 2) becomes

$$A_S(t) = \int_0^t K_2 t \, dt = \frac{1}{2} K_2 t^2 \quad . \quad (\text{ID. 6})$$

Equations (ID. 1) and (ID. 6) yield the approximation

$$n_c = \frac{2A \times (5280)^2}{K_2 t^2} \quad , \quad (\text{ID. 7})$$

for spread Case 2.

## APPENDIX II

### RATIONALE FOR SENSITIVITY ANALYSIS

#### II. 1 Purpose

To examine the sensitivity of the radial inrush wind velocity, as calculated in Appendix IA, to variations in seven selected parameters, expressions for the partial derivatives  $\frac{\partial v_w}{\partial \mu_i}$  have been developed, where  $\mu_1 = n$ ,  $\mu_2 = A$ ,  $\mu_3 = FL$ ,  $\mu_4 = E_{\text{fuel}}$ ,  $\mu_5 = E_{\text{frac, viol}}$ ,  $\mu_6 = E_{\text{frac, resid}}$ , and  $\mu_7 = r$ .

#### II. 2 Partial Derivatives

Formulae for the partial derivatives with respect to selected parameters have been derived as follows:

For convenience, let us represent Eq. (IA. 1) as

$$v_w = Q_1 \cdot Q_2 \cdot Q_3 \quad (\text{II. 1})$$

where

$$Q_1 = \left( \frac{88}{1000} \right) \left( \frac{50}{1089} \right)^{1/3}, \quad (\text{II. 2})$$

$$Q_2 = \frac{[(n)(FL)(E_{\text{fuel}})]^{1/3}}{A^{1/6}}, \quad (\text{II. 3})$$

and

$$Q_3 = \left\{ \frac{A_{SV}(r, t, \Delta t_V) \cdot E_{\text{frac, viol}}}{\Delta t_V} + \frac{A_{SR}(r, t, \Delta t_V, \Delta t_R) \cdot E_{\text{frac, resid}}}{\Delta t_R} \right\}^{1/3}. \quad (\text{II. 4})$$

Then

$$\frac{\partial v_w}{\partial n} = Q_1 Q_3 \frac{[(FL)(E_{fuel})]^{1/3}}{3n^{2/3} A^{1/6}} \quad (II. 5)$$

$$\frac{\partial v_w}{\partial A} = \frac{Q_1 Q_3 [(n)(FL)(E_{fuel})]^{1/3}}{-6 A^{7/6}} \quad (II. 6)$$

$$\frac{\partial v_w}{\partial (FL)} = \frac{Q_1 Q_3 [(n)(E_{fuel})]^{1/3}}{3(FL)^{2/3} A^{1/6}} \quad (II. 7)$$

$$\frac{\partial v_w}{\partial (E_{fuel})} = \frac{Q_1 Q_3 [(n)(FL)]^{1/3}}{3(E_{fuel})^{2/3} A^{1/6}} \quad (II. 8)$$

$$\frac{\partial v_w}{\partial (E_{frac, viol})} = \frac{Q_1 Q_2}{3(Q_3)^2} \left( \frac{A_{SV}(r, t, \Delta t_V)}{\Delta t_V} - \frac{A_{SR}(r, t, \Delta t_V, \Delta t_R)}{\Delta t_R} \right) \quad (II. 9)$$

and

$$\frac{\partial v_w}{\partial (E_{frac, resid})} = \frac{Q_1 Q_2}{3(Q_3)^2} \left( \frac{A_{SR}(r, t, \Delta t_V, \Delta t_R)}{\Delta t_R} - \frac{A_{SV}(r, t, \Delta t_V)}{\Delta t_V} \right) \quad (II. 10)$$

Note that

$$\frac{\partial v_w}{\partial (E_{frac, viol})} = - \frac{\partial v_w}{\partial (E_{frac, resid})} \quad (II. 11)$$

For Case 1, if  $t \leq \Delta t_V$ ,

$$\frac{\partial v_w}{\partial r} = \frac{Q_1 Q_2}{3(Q_3)^2} \left( \frac{t \cdot E_{frac, viol}}{\Delta t_V} \right) \quad (II. 12)$$

If  $\Delta t_V < t \leq \Delta t_V + \Delta t_R$  ,

$$\frac{\partial v_w}{\partial r} = \frac{Q_1 Q_2}{3(Q_3)^2} \left[ E_{\text{frac, viol}} + \frac{(t - \Delta t_V) \cdot E_{\text{frac, resid}}}{\Delta t_R} \right] , \quad (\text{II. 13})$$

and if  $t > \Delta t_V + \Delta t_R$  ,

$$\frac{\partial v_w}{\partial r} = \frac{Q_1 Q_2}{3(Q_3)^2} \left( E_{\text{frac, viol}} + E_{\text{frac, resid}} \right) . \quad (\text{II. 14})$$

Since

$$E_{\text{frac, viol}} + E_{\text{frac, resid}} = 1 , \quad (\text{II. 15})$$

then

$$\frac{\partial v_w}{\partial r} = \frac{Q_1 Q_2}{3(Q_3)^2} . \quad (\text{II. 16})$$

For Case 2, if  $t \leq \Delta t_V$  ,

$$\frac{\partial v_w}{\partial r} = \frac{Q_1 Q_2}{6(Q_3)^2} \left( \frac{t \cdot E_{\text{frac, viol}}}{\Delta t_V} \right) . \quad (\text{II. 17})$$

If  $\Delta t_V < t \leq \Delta t_V + \Delta t_R$  ,

$$\frac{\partial v_w}{\partial r} = \frac{Q_1 Q_2}{6(Q_3)^2} \left\{ \left[ 2 - (\Delta t_V / t) \right] E_{\text{frac, viol}} + \left[ \frac{t - 2\Delta t_V + (\Delta t_V^2 / t)}{\Delta t_R} \right] E_{\text{frac, resid}} \right\} . \quad (\text{II. 18})$$

and if  $t > \Delta t_V + \Delta t_R$ ,

$$\frac{\partial v_w}{\partial r} = \frac{Q_1 Q_2}{6(Q_3)^2} \left\{ \left[ 2 - (\Delta t_V/t) \right] E_{\text{frac, viol}} + \left[ 2 - \frac{2(\Delta t_V) + \Delta t_R}{t} \right] E_{\text{frac, resid}} \right\} . \quad (\text{II. 19})$$

### II. 3 Input Parameters

Calculations have been made of  $\frac{\partial v_w}{\partial \mu_i}$ ,  $i=1, \dots, 7$ , using fixed representative values of  $\mu_j$  ( $j \neq i$ ) and varying  $\mu_i$  across a range.

Representative values, ranges, and points of calculation are listed in Table II-I.

### II. 4 Method of Calculations

A computer program was written based upon Eqs. (II. 2),  $\dots$ , (II. 19) and run using the input parameters as defined in Table II-I. A listing of this program and a sample of its output is included in Appendix III.

Appendix V contains seven sets of sensitivity curves based upon the output of this program. Each set represents  $\frac{\partial v_w}{\partial \mu_i}$  plotted as a function of  $\mu_i$  for each time value.

TABLE II - I  
INPUT VALUES FOR SENSITIVITY ANALYSIS

Parameter	Representative Value	Range	Points
$n_d$	4500	2K - 10K	2K, 3K, 4K, 4.5K, 5K, 6K, 7K, and 10K
FL	15.0 T/Ac	5 - 30 T/Ac	5, 15.0, 30 T/Ac
$E_{fuel}$	7000 Btu/lb	6000 - 9000	6K, 7K, 8K, 9K
A	15.0 mi <sup>2</sup>	1.0 - 25.0 mi <sup>2</sup>	1.0, 5.0, 10.0 15.0, 25.0 mi <sup>2</sup>
t	--	(Same as in Section IA. 4)	
$\Delta t_V$	360 sec	--	--
r	(Case 2-b)		
M	.01 ft/sec	.005 - .2 ft/sec	.005, .01, .015, .2
L	.1 ft/sec	--	--
$K_1$	5.0 ft <sup>2</sup> /sec	--	--
$A_{SV}$	(Use Table IA-II)		
$E_{frac, viol}$	0.4	0.2 - 0.8	0.2, 0.4, 0.6, 0.8
$\Delta t_R$	4200 sec	--	--
$A_{SR}$	(Use Table IA-II)		
$E_{frac, resid}$	0.6	0.2 - 0.8	0.2, 0.4, 0.6, 0.8



### APPENDIX III

#### COMPUTER PROGRAM FOR INRUSH WIND AND SENSITIVITY CALCULATIONS

##### III.1 General

The following program is in two parts. Part I calculates  $v_w$  as a function of time and  $n$  for each combination of the other input variables as defined in Section IA.4. Part II calculates  $\frac{\partial v_w}{\partial \mu_i}$  ( $i = 1, \dots, 7$ ) as a function of  $\mu_i$  and time, with  $\mu_j$  ( $j \neq i$ ) held constant, as discussed in Section II.4. The inputs for Part II are listed in Table II-I. The program is written in FORTRAN IV for an IBM System/360 Model 40G digital computer.

##### III.2 Data Cards

Thirteen data cards are required. The first six data cards contain the input data for Part I of the program. Card 1 has format 8F10.4 and contains the following variables:

<u>Columns</u>	<u>Parameter</u>	<u>Program Symbol</u>	<u>Units</u>
1-10	$E_{\text{fuel}}$	EF	Btu/lb
11-20	$\Delta t_V$	DTV	seconds
21-30	$\Delta t_R$	DTR	seconds
31-40	$E_{\text{frac, viol}}$	EFV	number
41-50	$E_{\text{frac, resid}}$	EFR	number

Card 2 has format 3F10.6 and contains, in cols. 1-10, the rate of area spread in square feet per second; in cols. 11-20, the rate of perimeter increase in feet per second; and in cols. 21-30, the rate of radial increase in feet per second.

Card 3 has format 8F10.4 and contains three values of fuel loading in tons per acre.

Card 4 has format 8F10.4 and contains five values of area in square miles.

Card 5 has format 8I8 and contains eight values of initial ignition density ( $n_d$ ) in number per square mile.

Cards 6 and 7 have format 8F10.4 and contain ten values of time in seconds.

Card 8 has format 8I8 and is a flag card. If one wishes to perform the sensitivity calculations of Part II, an integer 2 should be put in col. 8. If one wishes to omit the sensitivity calculations, an integer 1 should be put in col. 8.

The last five cards contain the additional inputs needed for Part II of the program. Card 7 has format I8, 6F10.4 and contains the representative values of the seven  $\mu_i$  arranged in the following manner:

<u>Columns</u>	<u>Parameter</u>	<u>Program Symbol</u>	<u>Units</u>
1- 8	Rep. value of $n_d$	NDR	number
9-18	Rep. value of A	AR	square miles
19-28	Rep. value of FL	FLR	tons/acre
29-38	Rep. value of $E_{\text{fuel}}$	EFP	Btu/lb
39-48	Rep. value of $E_{\text{frac, viol}}$	EFVR	number
49-58	Rep. value of $E_{\text{frac, resid}}$	EFRR	number
59-68	Rep. value of M	AMR	feet/second

Cards 10-13 have format 4F10.5 and contain the points across the range of the four  $\mu_i$  which were used as constant in Part I.

<u>Card</u>	<u>Parameter</u>	<u>Program Symbol</u>	<u>No. of Points</u>	<u>Units</u>
8	$E_{\text{fuel}}$	EF2(I)	4	Btu/lb
9	$E_{\text{frac, viol}}$	EFV2(I)	4	number
10	$E_{\text{frac, resid}}$	EFR2(I)	4	number
11	M (radial spread rate)	AM2(I)	4	feet/second

### III. 3 Program Listing

(See following pages.)

	DIMENSION A(5),T(10),N(8),CN(8),FL(3),NC(10),ND(8),VW(10,8),TM(10)	1
	DIMENSION EF2(4),EFV2(4),EFR2(4),AM2(4),ASVR(10),ASRR(10),Q3(10)	2
	\$,PVW(8,10),NA(8)	3
C	PART ONE CALCULATES THE SET OF RADIAL INDRAFT WIND VELOCITIES	4
C	RESULTING FROM 8 VALUES OF N, THE NUMBER OF INITIAL FIRES, AT 10	5
C	GIVEN TIMES AFTER IGNITION. THIS SET IS PRODUCED FOR COMBINATIONS	6
C	OF 3 FUEL LOADINGS, 5 AREAS, AND 3 TYPES OF FIRE SPREAD.	7
C	THE FOLLOWING ARE INPUT VARIABLES:	8
C	EF, ENERGY CONTENT OF FUEL (BTU/POUND); DTV, VIOLENT BURNING TIME	9
C	(SECONDS); EFV, VIOLENT BURNING FRACTION; DTR, RESIDUAL BURNING TIME	10
C	(SECONDS); EFR, RESIDUAL BURNING FRACTION; AK, RATE OF AREA CHANGE,	11
C	(SQUARE FEET/SEC); AL, RATE OF PERIMETER CHANGE (FEET/SEC); AM,	12
C	RATE OF RADIUS CHANGE (FEET/SEC); FL(3), FUEL LOADINGS (TONS/ACRE);	13
C	A(5), AREAS (SQUARE MILES); ND(8), NUMBER OF INITIAL FIRES PER SQUAR	14
C	MILE (NUMBER/MILES SQUARED); T(10), TIMES AFTER IGNITION (SECONDS).	15
1	FORMAT (8F10.4)	16
2	FORMAT (8I8)	17
3	FORMAT (3F10.6)	18
	READ (1,1) EF,DTV,DTR,EFV,EFR	19
	READ (1,3) AK,AL,AM	20
	READ (1,1) (FL(I),I=1,3)	21
	READ (1,1) (A(I),I=1,5)	22
	READ (1,2) (ND(I),I=1,8)	23
	READ (1,1) (T(I),I=1,10)	24
	AK2=(AL*AL)/6.28318	25
	AK3=(AM*AM)*6.28318	26
	FMF=2.78784E+07	27
	FDV=EFV/DTV	28
	EDR=EFR/DTR	29
	DTVR=DTV+DTR	30
C	ICASE INDICATES WHICH TYPE OF FIRE SPREAD IS BEING USED:	31
C	1 = CONSTANT AREA CHANGE; 2 = CONSTANT PERIMETER CHANGE;	32
C	3 = CONSTANT RADIAL CHANGE.	33
	DO 45 ICASF=1,3	34
	IF (ICASE-2) 6,4,5	35
4	CONST=AK2	36
	GO TO 6	37
5	CONST=AK3	38
C	M INDEXES OVER THE 3 FUEL LOADINGS. L INDEXES OVER THE 5 AREAS	39
6	DO 45 M=1,3	40
	DO 45 L=1,5	41
	DO 7 I=1,8	42
	N(I)=ND(I)*A(L)	43
	CN(I)=N(I)**(1.0/3.0)	44
	AA=((FL(M)*EF)**(1.0/3.0))/(A(L)**(1.0/6.0))*0.031501	45
C	STATEMENTS 8-15 COMPUTE VELOCITIES FOR ICASE=1.	46
	IF (ICASE-1) 8,8,16	47
8	R=AK	48
	DO 15 K=1,10	49
	TIME=T(K)	50
	IF (TIME-DTV) 9,9,10	51
9	ASV=R*TIME	52

	ASR=0.0	53
	ASB0=0.0	54
	GO TO 13	55
10	IF (TIME-DTVR) 11,11,12	56
11	ASV=R*DTV	57
	ASR=R*(TIME-DTV)	58
	ASB0=0.0	59
	GO TO 13	60
12	ASV=R*DTV	61
	ASR=R*DTR	62
	ASB0=R*(TIME-DTVR)	63
13	AAA=AA*((ASV*EDV+ASR*EDR)**(1.0/3.0))	64
	DO 14 I=1,8	65
14	VW(K,I)=AAA*CN(I)	66
15	NC(K)=A(L)/(AK*TIME)*FMF	67
	GO TO 24	68
C	STATEMENTS 16-23 COMPUTE VELOCITIES FOR ICASE=2 OR 3.	69
16	DO 23 K=1,10	70
	TIME=T(K)	71
	R=CONST*TIME	72
	RH=R/2.0	73
	IF (TIME-DTV) 17,17,18	74
17	ASV=RH*TIME	75
	ASR=0.0	76
	ASB0=0.0	77
	GO TO 21	78
18	IF (TIME-DTVR) 19,19,20	79
19	ASV=RH*(DTV*(2.0-(DTV/TIME)))	80
	ASR=RH*(TIME-DTV*(2.0-DTV/TIME))	81
	ASB0=0.0	82
	GO TO 21	83
20	ASV=RH*DTV*(2.0-DTV/TIME)	84
	ASR=RH*DTR*(2.0-(2.0*DTV+DTR)/TIME)	85
	ASB0=RH*(TIME-DTVR*(2.0-DTVR/TIME))	86
21	AAA=AA*((ASV*EDV+ASR*EDR)**(1.0/3.0))	87
	DO 22 I=1,8	88
22	VW(K,I)=AAA*CN(I)	89
23	NC(K)=(2.0*A(L))/(CONST*TIME*TIME)*FMF	90
24	WRITE (3,25)	91
25	FORMAT ('1',T39,'VW IS THE RADIAL INDRAFT WIND VELOCITY IN MILES P ER HOUR'/'0',T23,'N IS THE NUMBER OF INITIAL FIRES, NC IS THE REQU \$IRED N FOR COALESCENCE BY THE GIVEN TIME'//)	92 93 94
	C=DTV/60.0	95
	B=DTR/60.0	96
	WRITE (3,26) EF,EFV,EFR,C,B	97
26	FORMAT ('0',T41,'ENERGY CONTENT OF THE FUEL IS ',F9.1,' BTU PER PO UND'/'0',T9,'VIOLENT BURNING FRACTION IS ',F6.2,T85,'RESIDUAL BUR \$NING FRACTION IS ',F6.2/1X,T9,'VIOLENT BURNING TIME IS ',F6.2,' MI \$NUTES',T85,'RESIDUAL BURNING TIME IS ',F6.2,' MINUTES'//)	98 99 100 101
	IF (ICASE-2) 27,28,29	102
27	WRITE (3,30) AK	103
	GO TO 33	104

28	WRITE (3,31) AL	105
	GO TO 33	106
29	WRITE (3,32) AM	107
30	FORMAT ('0',T32,'CASE 1, CONSTANT AREA INCREASE, K = ',E13.6,' (SQ	108
	SUARE FEET/SECOND)')//)	109
31	FORMAT ('0',T33,'CASE 2A, CONSTANT PERIMETER INCREASE, L = '	110
	\$,E13.6,' (FEET/SECOND)')//)	111
32	FORMAT ('0',T34,'CASE 2B, CONSTANT RADIAL INCREASE, M = ',E13.6,'	112
	\$(FEET/SECOND)')//)	113
33	WRITE (3,34) A(L),FL(M)	114
34	FORMAT ('0',T26,'AREA = ',F10.4,' SQUARE MILES ',10X,' FUEL LOADING	115
	\$G = ',F10.4,' TONS PER ACRE')//)	116
	DO 35 I=1,10	117
35	TM(I)=T(I)/60.0	118
	DO 40 II=1,2	119
	IF (II-1) 36,36,37	120
36	IA=1	121
	IB=5	122
	GO TO 38	123
37	IA=6	124
	IB=10	125
38	WRITE (3,41) (TM(I),I=IA,IB)	126
	WRITE (3,42)	127
	DO 39 K=1,8	128
39	WRITE (3,43) (N(K),VW(I,K),I=IA,IB)	129
40	WRITE (3,44) (NC(I),I=IA,IB)	130
41	FORMAT ('0',T4,5(4X,' FOR ',F6.1,' MINUTES ')//)	131
42	FORMAT ('0',T4,5(6X,'N',11X,'VW',4X)//)	132
43	FORMAT (1X,T4,5(3X,16,2X,E13.6))	133
44	FORMAT ('0',T4,5(7X,'NC =',110,3X)////)	134
45	CONTINUE	135
	READ (1,2) N2	136
	IF (N2-2) 103,46,103	137
C	PART TWO CALCULATES THE PARTIAL DERIVATIVES WITH RESPECT TO THE	138
C	FOLLOWING VARIABLES: N,A,FL,EF,EFFV,EFR,R. EACH PARTIAL IS EVALUATED	139
C	FOR ALL THE INPUT VALUES OF THE VARIABLE AND AT EACH OF THE TIMES	140
C	USED IN PART ONE.	141
C	ADDITIONAL INPUT NEEDED FOR PART TWO IS:	142
C	NDR,AR,FLR,FFP,FFVR,FFRR,AMP (THESE ARE MOST PROBABLE OR REPRESENTAT	143
C	VALUES FOR THE VARIABLES FOR WHICH THE PARTIALS ARE EVALUATED.)	144
C	EF2(4), ENERGY CONTENT OF THE FUEL(BTU/POUND); FFV2(4), VIOLENT	145
C	BURNING FRACTION; FFR2(4), RESIDUAL BURNING FRACTION; AM2(4), RATE	146
C	OF RADIAL INCREASE(FEET/SEC).	147
46	READ (1,47) NDR,AR,FLR,FFP,FFVR,FFRR,AMP	148
47	FORMAT (18,6F10.2)	149
	READ (1,48) (EF2(I),I=1,4)	150
	READ (1,48) (FFV2(I),I=1,4)	151
	READ (1,48) (FFR2(I),I=1,4)	152
	READ (1,48) (AM2(I),I=1,4)	153
48	FORMAT (4F10.5)	154
C	THROUGH 53 CALCULATES Q3, THE PART OF THE PARTIALS WHICH IS ONLY	155
C	TIME-DEPENDENT	156

	AK2=AMR*AMR*6.28318	157
	DO 53 K=1,10	158
	TIME=T(K)	159
	RRH=AK2*TIME/2.0	160
	IF (TIME-DTV) 49,49,50	161
49	ASVR(K)=RRH*TIME	162
	ASRR(K)=0.0	163
	GO TO 53	164
50	IF (TIME-DTVR) 51,51,52	165
51	ASVR(K)=RRH*(DTV*(2.0-DTV/TIME))	166
	ASRR(K)=RRH*(TIME-DTV*(2.0-DTV/TIME))	167
	GO TO 53	168
52	ASRR(K)=RRH*(DTR*(2.0-((2.0*DTV+DTR)/TIME)))	169
	ASVR(K)=RRH*(DTV*(2.0-DTV/TIME))	170
53	Q3(K)=((ASVR(K)*EFVR/DTV)+(ASRR(K)*EFRR/DTR))*((1.0/3.0)	171
C	PARTIALS WITH RESPECT TO N(NUMBER OF INITIAL FIRES) FOR 8 N	172
	BB=.031501*((FLR*EFP)**(1.0/3.0)/(3.0*(AR**((1.0/6.0))))	173
	DO 54 I=1,8	174
	BBB=BB/(ND(I)*AR)**(2.0/3.0)	175
	DO 54 K=1,10	176
54	PVW(I,K)=BBB*Q3(K)	177
55	FORMAT ('1',T40,'PARTIAL DERIVATIVES OF THE RADIAL INDRAFT WIND VE	178
	\$LOCITY')	179
56	FORMAT (1X,T44,'WITH RESPECT TO N, THE NUMBER OF INITIAL FIRES')	180
57	FORMAT (1X,T31,'FOR CASE 28, CONSTANT RADIAL INCREASE, M = '	181
	\$,E13.6,' FEET PER SECOND'//)	182
58	FORMAT ('0',T4,'WITH AREA = ',F10.5,' SQUARE MILES FUEL LOADING	183
	\$G = ',F10.4,' TONS PER ACRE ENERGY OF FUEL = ',F10.4,' BTU PER	184
	\$ POUND')	185
59	FORMAT (1X,T9,'VIOLENT BURNING FRACTION = ',F6.2,T85,'RESIDUAL BUR	186
	\$NING FRACTION = ',F6.2)	187
60	FORMAT (1X,T9,'VIOLENT BURNING TIME = ',F6.2,' MINUTES',T85,'RESID	188
	\$UAL BURNING TIME = ',F6.2,' MINUTES'/////)	189
61	FORMAT ('0',T15,'N =',8(3X,I8,3X))	190
62	FORMAT ('0',T3,F6.1,' MINUTES ',8(1X,E13.6))	191
	WRITE (3,55)	192
	WRITE (3,56)	193
	WRITE (3,57) AMR	194
	WRITE (3,58) AR,FLR,EFP	195
	WRITE (3,59) EFVR,EFRR	196
	WRITE (3,60) C,B	197
	DO 63 I=1,8	198
63	NA(I)=ND(I)*AR	199
	WRITE (3,61) (NA(I),I=1,8)	200
	DO 64 K=1,10	201
64	WRITE (3,62) TM(K),(PVW(I,K),I=1,9)	202
C	PARTIALS WITH RESPECT TO A(AREA) FOR 5 A	203
	BB=.031501*(FLR*EFP)**(1.0/3.0)	204
	DO 65 I=1,5	205
	BBB=BB*(NDR*AR)**(1.0/3.0)/(-6.0*A(I)**(7.0/6.0))	206
	DO 65 K=1,10	207
65	PVW(I,K)=BBB*Q3(K)	208

	NR=NDR*AR	209
	WRITE (3,55)	210
	WRITE (3,66)	211
66	FORMAT (1X,T51,'WITH RESPECT TO A, THE TOTAL AREA')	212
	WRITE (3,57) AMR	213
	WRITE (3,67) NR,FLR,FFP	214
67	FORMAT ('0',T4,'WITH INITIAL NUMBER OF FIRES = ',I8,3X,'FUEL LOADI	215
	\$NG = ',F10.4,' TONS PER ACRE',3X,'ENERGY OF FUEL = ',F10.4,' BTU P	216
	\$ER POUND')	217
	WRITE (3,59) EFVR,EFRR	218
	WRITE (3,60) C,R	219
	WRITE (3,69) (A(I),I=1,5)	220
	DO 68 K=1,10	221
68	WRITE (3,70) TM(K),(PVW(I,K),I=1,5)	222
69	FORMAT ('0',T19,'A = ',5(8X,F10.5,2X)/1X,T13,' (SQUARE MILES)')//)	223
70	FORMAT ('0',T7,F6.1,' MINUTES ',5(7X,E13.6))	224
C	PARTIALS WITH RESPECT TO FL(FUEL LOADING) FOR 3 FL	225
	BB=.031501*(NDR*AR*FFP)**(1.0/3.0)/(3.0*AR**(1.0/6.0))	226
	DO 71 I=1,3	227
	BBB=BB/FL(I)**(2.0/3.0)	228
	DO 71 K=1,10	229
71	PVW(I,K)=BBB*Q3(K)	230
	WRITE (3,55)	231
	WRITE (3,72)	232
72	FORMAT (1X,T49,'WITH RESPECT TO FL, THE FUEL LOADING')	233
	WRITE (3,57) AMR	234
	WRITE (3,73) NR,AR,FFP	235
73	FORMAT ('0',T4,'WITH INITIAL NUMBER OF FIRES = ',I8,5X,'AREA = '	236
	\$,F10.5,' SQUARE MILES',5X,'ENERGY OF FUEL = ',F10.4,' BTU PER POUN	237
	\$D')	238
	WRITE (3,59) EFVR,EFRR	239
	WRITE (3,60) C,R	240
	WRITE (3,75) (FL(I),I=1,3)	241
	DO 74 K=1,10	242
74	WRITE (3,76) TM(K),(PVW(I,K),I=1,3)	243
75	FORMAT ('0',T32,'FL = ',3(11X,F10.4,2X)/1X,T26,'(TONS PER ACRE)')//)	244
76	FORMAT ('0',T22,F6.1,' MINUTES ',3(10X,E13.6))	245
C	PARTIALS WITH RESPECT TO FF(ENERGY CONTENT OF FUEL) FOR 4 EF	246
	BR=(.031501*(NDR*AR*FLR)**(1.0/3.0))/(3.0*AR**(1.0/6.0))	247
	DO 77 I=1,4	248
	BBB=BR/FF2(I)**(2.0/3.0)	249
	DO 77 K=1,10	250
77	PVW(I,K)=BBB*Q3(K)	251
	Q12=.031501*(NDR*AR*FLP*FFP)**(1.0/3.0)/AR**(1.0/6.0)	252
	WRITE (3,55)	253
	WRITE (3,78)	254
78	FORMAT (1X,T42,'WITH RESPECT TO FF, THE ENERGY CONTENT OF THE FUEL	255
	\$')	256
	WRITE (3,57) AMR	257
	WRITE (3,79) NR,AR,FLP	258
79	FORMAT ('0',T4,'WITH INITIAL NUMBER OF FIRES = ',I8,5X,'AREA = '	259
	\$,F10.5,' SQUAPE MILES',5X,'FUEL LOADING = ',F10.4,' TONS PER ACRE'	260



	\$)	261
	WRITE (3,59) EFVR,EFR	262
	WRITE (3,60) C,R	263
	WRITE (3,80) (EF2(I),I=1,4)	264
80	FORMAT ('0',T25,'EF =',4(11X,F10.5,2X)/1X,T17,'(BTU PER POUND)')//)	265
	DO 81 K=1,10	266
81	WRITE (3,82) TM(K),(PVW(I,K),I=1,4)	267
82	FORMAT ('0',T14,F6.1,' MINUTES ',4(10X,E13.6))	268
C	PARTIALS WITH RESPECT TO EFV(VIOLENT BURNING FRACTION) FOR 4 EFV2	269
	DO 83 I=1,4	270
	EFRC=1.0-EFV2(I)	271
	DO 83 K=1,10	272
	AAA=ASVR(K)/DTV	273
	BBB=ASRR(K)/DTR	274
83	PVW(I,K)=Q12*(AAA-BBB)/(3.0*(AAA*EFV2(I)+BBB*EFRC)**(2.0/3.0))	275
	WRITE (3,55)	276
	WRITE (3,84)	277
84	FORMAT (1X,T42,'WITH RESPECT TO EFV, THE VIOLENT BURNING FRACTION'	278
	\$)	279
	WRITE (3,57) AMR	280
	WRITE (3,79) NR,AR,FLR	281
	WRITE (3,85) EFP	282
85	FORMAT (1X,T9,'ENERGY OF FUEL =',F10.4,' BTU PER POUND',T85,'RESI	283
	DUAL BURNING FRACTION = 1.0-EFV')	284
	WRITE (3,60) C,R	285
	WRITE (3,87) (EFV2(I),I=1,4)	286
	DO 86 K=1,10	287
86	WRITE (3,82) TM(K),(PVW(I,K),I=1,4)	288
87	FORMAT ('0',T24,'EFV =',4(11X,F10.5,2X)//)	289
C	PARTIALS WITH RESPECT TO EFR(RESIDUAL BURNING FRACTION) FOR 4 EFR2	290
	DO 88 I=1,4	291
	EFVC=1.0-EFR2(I)	292
	DO 88 K=1,10	293
	BBB=ASRR(K)/DTR	294
	AAA=ASVR(K)/DTV	295
88	PVW(I,K)=Q12*(BBB-AAA)/(3.0*(AAA*EFVC+BBB*EFR2(I))**(2.0/3.0))	296
	WRITE (3,55)	297
	WRITE (3,89)	298
89	FORMAT (1X,T42,'WITH RESPECT TO EFR, THE RESIDUAL BURNING FRACTION	299
	\$')	300
	WRITE (3,57) AMR	301
	WRITE (3,79) NR,AR,FLR	302
	WRITE (3,90) EFP	303
90	FORMAT (1X,T9,'ENERGY OF FUEL =',F10.4,' BTU PER POUND',T85,'VIOLE	304
	NT BURNING FRACTION = 1.0-EFR')	305
	WRITE (3,60) C,R	306
	WRITE (3,92) (EFR2(I),I=1,4)	307
	DO 91 K=1,10	308
91	WRITE (3,82) TM(K),(PVW(I,K),I=1,4)	309
92	FORMAT ('0',T24,'EFR =',4(11X,F10.5,2X)//)	310
C	PARTIALS WITH RESPECT TO R(CASE 28) FOR 4 AM	311
	Q123=Q12*EFVR/DTV	312

	DO 97 I=1,4	313
	CONST=AM2(I)*AM2(I)*6.28318	314
	DO 97 K=1,10	315
	TIME=T(K)	316
	R=CONST*TIME/2.0	317
	IF (TIME-DTV) 93,93,94	318
93	PVW(I,K)=Q123*TIME/(6.0*(R*TIME*EFVR/DTV)**(2.0/3.0))	319
	GO TO 97	320
94	IF (TIME-DTVR) 95,95,96	321
95	BB=Q12*((2.0-DTV/TIME)*EFVR+((TIME-DTV*(2.0-DTV/TIME))/DTR*EFRR))	322
	QQ=(R*(DTV*(2.0-DTV/TIME))*EFVR/DTV)+(R*(TIME-DTV*(2.0-DTV/TIME))	323
	*EFRR/DTR)	324
	PVW(I,K)=BB/(6.0*QQ**(2.0/3.0))	325
	GO TO 97	326
96	BB=Q12*((2.0-DTV/TIME)*EFVR+((2.0-(DTR+DTV)/TIME)*EFRR))	327
	QQ=(R*DTV*(2.0-DTV/TIME)*EFVR/DTV)+(R*(DTR*(2.0-(2.0*DTV+DTR)	328
	/TIME))*EFRR/DTR)	329
	PVW(I,K)=BB/(6.0*QQ**(2.0/3.0))	330
97	CONTINUE	331
	WRITE (3,55)	332
	WRITE (3,98)	333
98	FORMAT (1X,T26,'WITH RESPECT TO R, THE RATE OF SPREAD, FOR CASE 28	334
	\$,R = 6.28*M**2*TIME')	335
	WRITE (3,99) AR,NR,FLR,EFV	336
99	FORMAT ('0',T14,'WITH AREA = ',F10.5,' SQUARE MILES',T75,'NUMBER O	337
	\$F INITIAL FIRES = ',I8/1X,T19,'FUEL LOADING = ',F10.4,' TONS PER A	338
	\$CRE',T75,'ENERGY OF FUEL = ',F10.5,' BTU PER POUND')	339
	WRITE (3,100) EFVR,EFRR,C,B	340
100	FORMAT (1X,T19,'VIOLENT BURNING FRACTION = ',F6.2,T75,'RESIDUAL BU	341
	\$RNING FRACTION = ',F6.2/1X,T19,'VIOLENT BURNING TIME = ',F6.2,' MI	342
	\$NUTES ',T75,'RESIDUAL BURNING TIME = ',F6.2,' MINUTES'////)	343
	WRITE (3,101) (AM2(I),I=1,4)	344
101	FORMAT ('0',T26,'M =',4(10X,F13.6)/1X,T18,'(FEET/SECOND)'///)	345
	DO 102 K=1,10	346
102	WRITE (3,82) TM(K),(PVW(I,K),I=1,4)	347
103	CONTINUE	348
	STOP	349
	END	350

Fig. III-1

SAMPLE OUTPUT PAGE FROM PART I

VM IS THE RADIAL INKRAFT WIND VELCCITY IN MILES PER HOUR  
N IS THE NUMBER OF INITIAL FIRES, NC IS THE REQUIRED N FOR COALESCENCE BY THE GIVEN TIME

ENERGY CONTENT OF THE FUEL IS 7000.0 BTU PER POUND

VILIENT BURNING FRACTION IS 0.60  
VILIENT BURNING TIME IS 0.60 MINUTES  
RESIDUAL BURNING FRACTION IS 0.60  
RESIDUAL BURNING TIME IS 70.00 MINUTES

CASE 20, CONSTANT RADIAL INCREASE, M = 0.100000E-01 (FEET/SECOND)

AREA = 15.0000 SQUARE MILES FUEL LOADING = 15.0000 TONS PER ACRE

2.0 MINUTES			4.0 MINUTES			6.0 MINUTES			8.0 MINUTES			16.0 MINUTES		
FUR	N	VM	FUR	N	VM	FUR	N	VM	FUR	N	VM	FUR	N	VM
10000	0.503648	01	30000	0.104773	02	30000	0.124576	02	30000	0.175383	02	30000	0.175383	02
45000	0.516588	01	45000	0.119935	02	45000	0.142604	02	45000	0.200764	02	45000	0.200764	02
60000	0.634617	01	60000	0.132006	02	60000	0.156556	02	60000	0.220969	02	60000	0.220969	02
67500	0.660048	01	67500	0.137291	02	67500	0.163241	02	67500	0.225817	02	67500	0.225817	02
75000	0.683620	01	75000	0.142199	02	75000	0.165075	02	75000	0.238032	02	75000	0.238032	02
80000	0.726459	01	80000	0.151109	02	80000	0.179659	02	80000	0.252946	02	80000	0.252946	02
105000	0.764759	01	105000	0.159076	02	105000	0.185143	02	105000	0.266283	02	105000	0.266283	02
150000	0.861308	01	150000	0.179159	02	150000	0.213022	02	150000	0.299901	02	150000	0.299901	02
NC = 7243734			NC = 23109344			NC = 10270817			NC = 5777334			NC = 1444334		

24.0 MINUTES			32.0 MINUTES			48.0 MINUTES			64.0 MINUTES			80.0 MINUTES		
FUR	N	VM	FUR	N	VM	FUR	N	VM	FUR	N	VM	FUR	N	VM
30000	0.210909	02	30000	0.240408	02	30000	0.290431	02	30000	0.338346	02	30000	0.373126	02
45000	0.241431	02	45000	0.275194	02	45000	0.332460	02	45000	0.382144	02	45000	0.427122	02
60000	0.282729	02	60000	0.302896	02	60000	0.369920	02	60000	0.420504	02	60000	0.470109	02
75000	0.317658	02	75000	0.315024	02	75000	0.380572	02	75000	0.437445	02	75000	0.488933	02
90000	0.342481	02	90000	0.326284	02	90000	0.394175	02	90000	0.453082	02	90000	0.506409	02
105000	0.364111	02	105000	0.346724	02	105000	0.418873	02	105000	0.481471	02	105000	0.538140	02
150000	0.410931	02	150000	0.365011	02	150000	0.440959	02	150000	0.506571	02	150000	0.566515	02
NC = 641921			NC = 361063			NC = 160481			NC = 90270			NC = 57773		

PARTIAL DERIVATIVES OF THE RADIAL INDRIFT WIND VELOCITY  
WITH RESPECT TO A, THE TOTAL AREA  
FOR CASE 2B, CONSTANT RADIAL INCREASE, M = 0.10000E-01 FEET PER SECOND

WITH INITIAL NUMBER OF FIRES = 67500 FUEL LOADING = 15.0000 TONS PER ACRE ENERGY OF FUEL = 7000.0000 BTU PER POUND  
VIOLENT BURNING FRACTION = 0.40 RESIDUAL BURNING FRACTION = 0.60  
VIOLENT BURNING TIME = 6.00 MINUTES RESIDUAL BURNING TIME = 70.00 MINUTES

Fig. III-2

SAMPLE OUTPUT PAGE FROM PART II

	A = (SQUARE MILES)	1.00000	5.00000	10.00000	15.00000	25.00000
2.0 MINUTES	-0.172753E 01	-0.264218E 00	-0.117696E 00	-0.733365E-01	-0.404108E-01	
4.0 MINUTES	-0.774229E 01	-0.419420E	-0.186830E 00	-0.116415E 00	-0.641481E-01	
6.0 MINUTES	-0.359341E 01	-0.549595E 00	-0.2444817E 00	-0.152546E 00	-0.840577E-01	
8.0 MINUTES	-0.427260E 01	-0.653473E 00	-0.291089E 00	-0.181379E 00	-0.999454E-01	
16.0 MINUTES	-0.601514E 01	-0.915987E 00	-0.409808E 00	-0.255353E 00	-0.140707E 00	
24.0 MINUTES	-0.723358E 01	-0.110634E 01	-0.492819E 00	-0.307077E 00	-0.169209E 00	
32.0 MINUTES	-0.824532E 01	-0.126106E 01	-0.561748E 00	-0.350027E 00	-0.192876E 00	
48.0 MINUTES	-0.990054E 01	-0.152348E 01	-0.678632E 00	-0.422858E 00	-0.233008E 00	
64.0 MINUTES	-0.114455E 02	-0.175115E 01	-0.780049E 00	-0.486051E 00	-0.267830E 00	
80.0 MINUTES	-0.127571E 02	-0.195726E 01	-0.871861E 00	-0.543260E 00	-0.299353E 00	

## APPENDIX IV

### RADIAL INRUSH WIND VELOCITY CURVES

The following 45 sets of curves are based upon the rationale and parameter values discussed in Appendix IA and are drawn from the output of Part I of the computer program listed in Appendix III.

Each curve on a page represents radial inrush wind velocity ( $v_w$ ) as a function of the number of initial ignitions ( $n$ ) for a specified time after ignition. Each family of curves shows ten different times with a specified combination of spread case, area, and fuel loading.

The curves are bounded above by the coalescence locus, as discussed in Appendix ID.

For all of the curves in this group, the fuel energy is taken as 7000 Btu/lb, the violent burning time as 6 minutes, the residual burning time as 70 minutes, the violent burning fraction as 0.4, and the residual burning fraction as 0.6 .

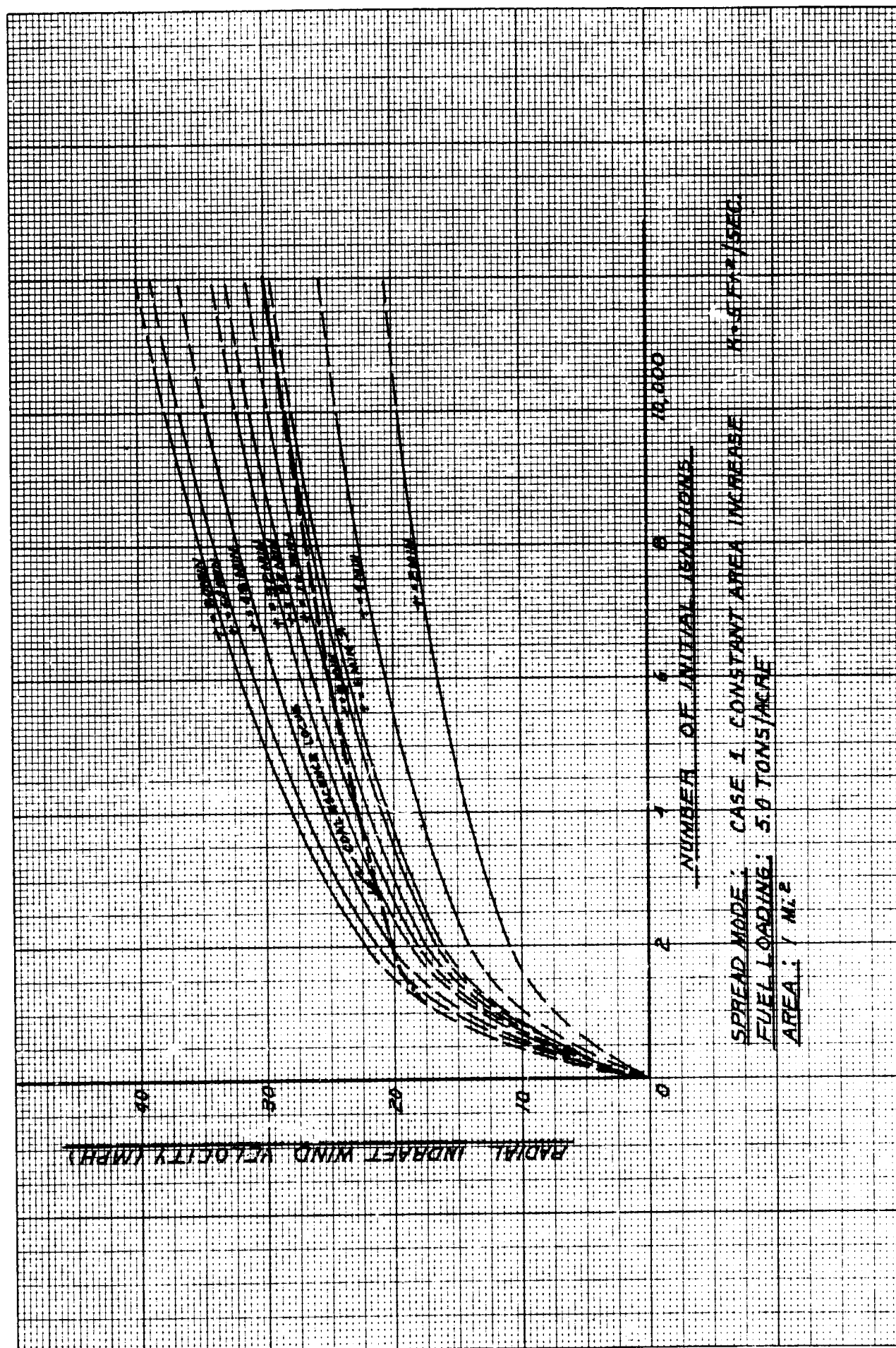


Fig. IV-1

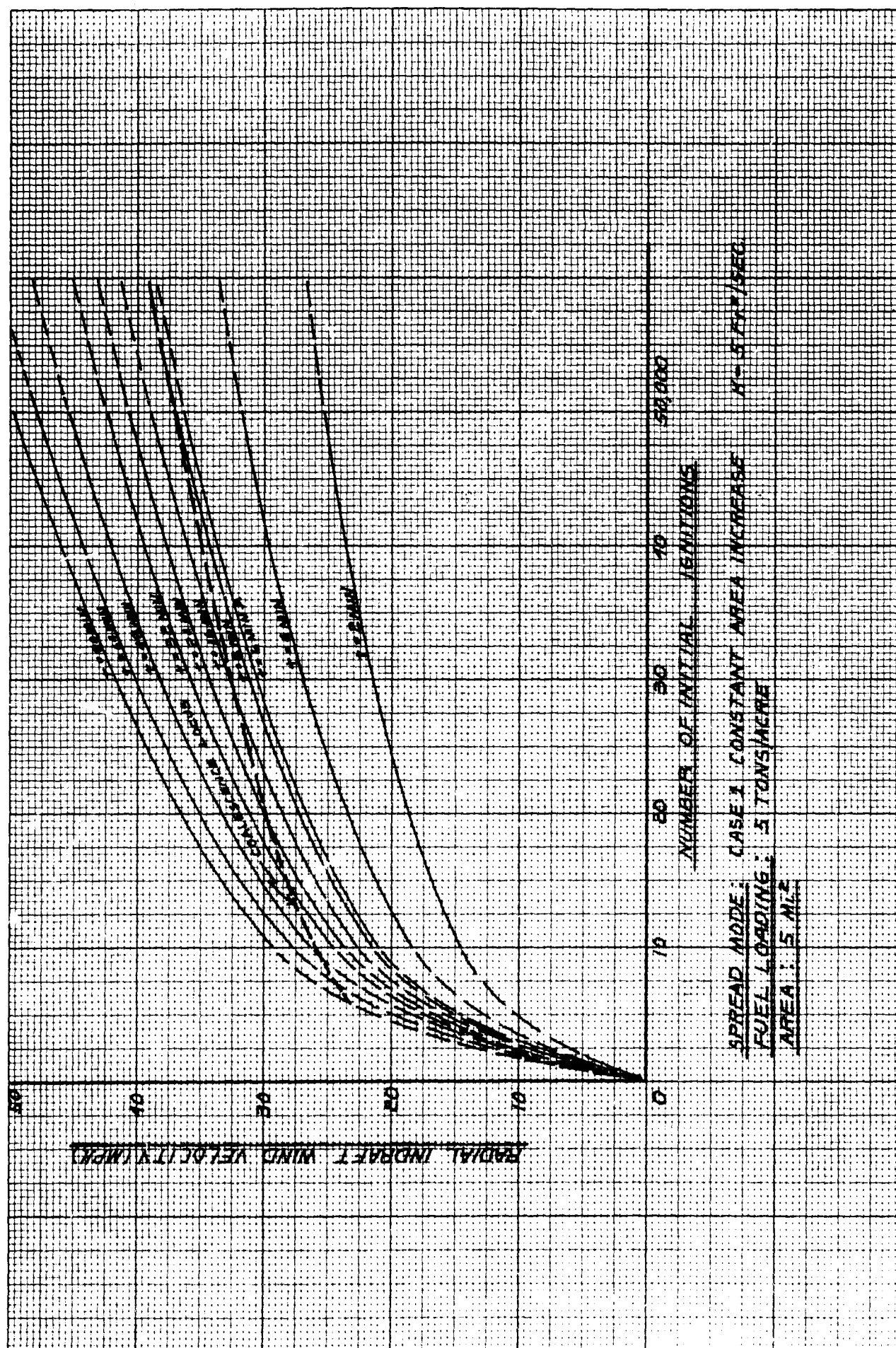


Fig. IV-2

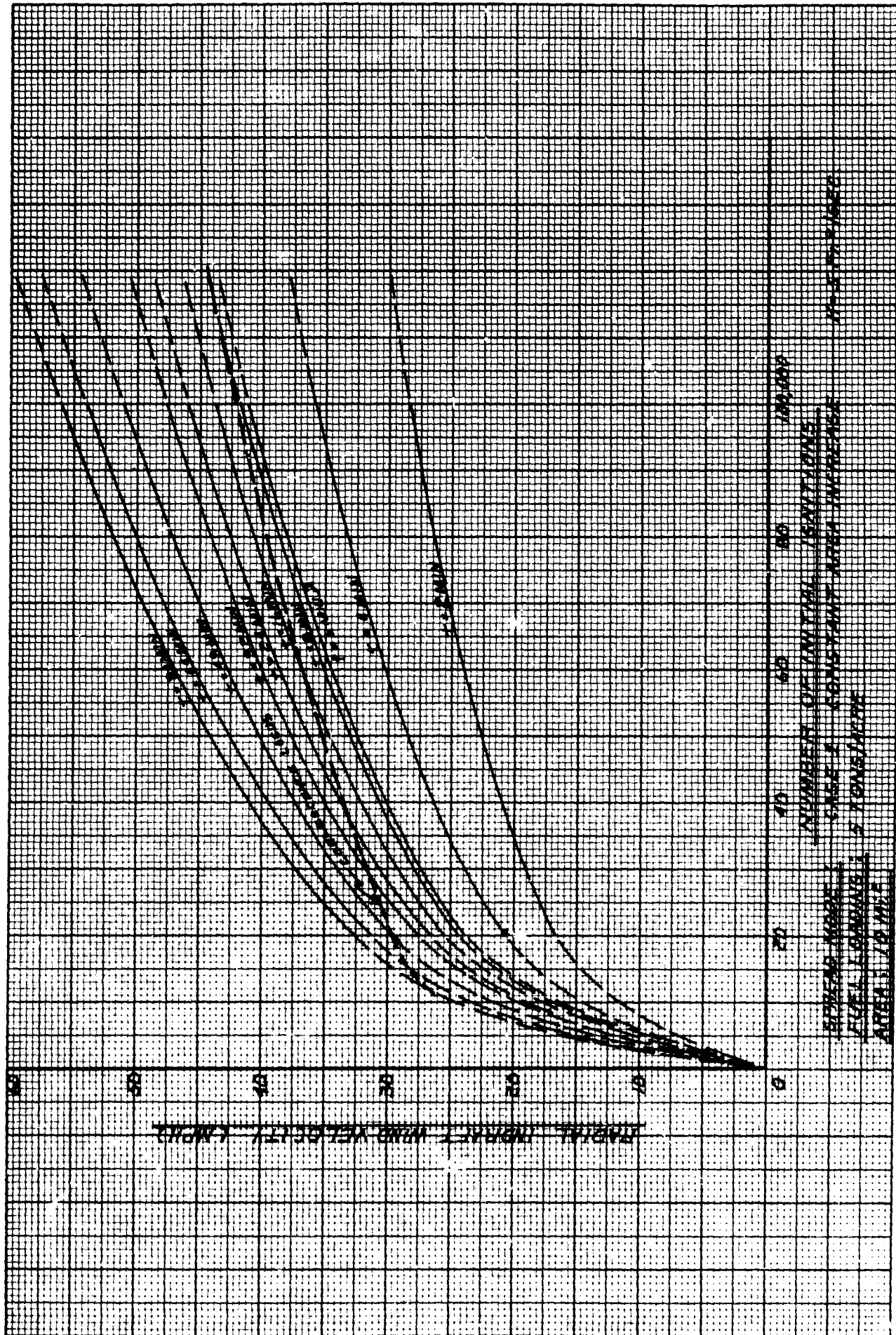


Fig. IV-3





FREDERICK POST COMPANY  
 JUTTEN CROSS SECTION 20 K 20 PER INCH

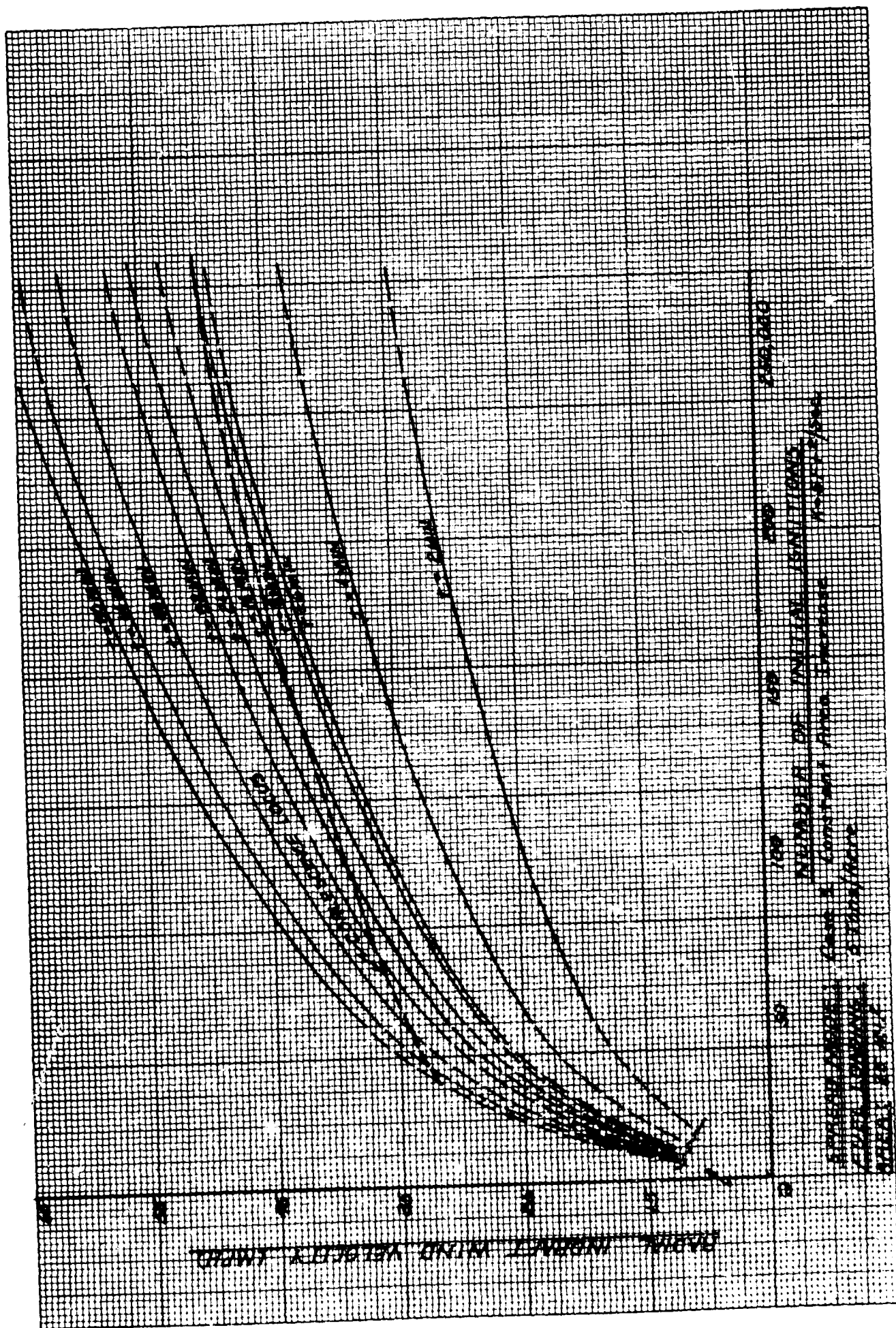


Fig. IV-5

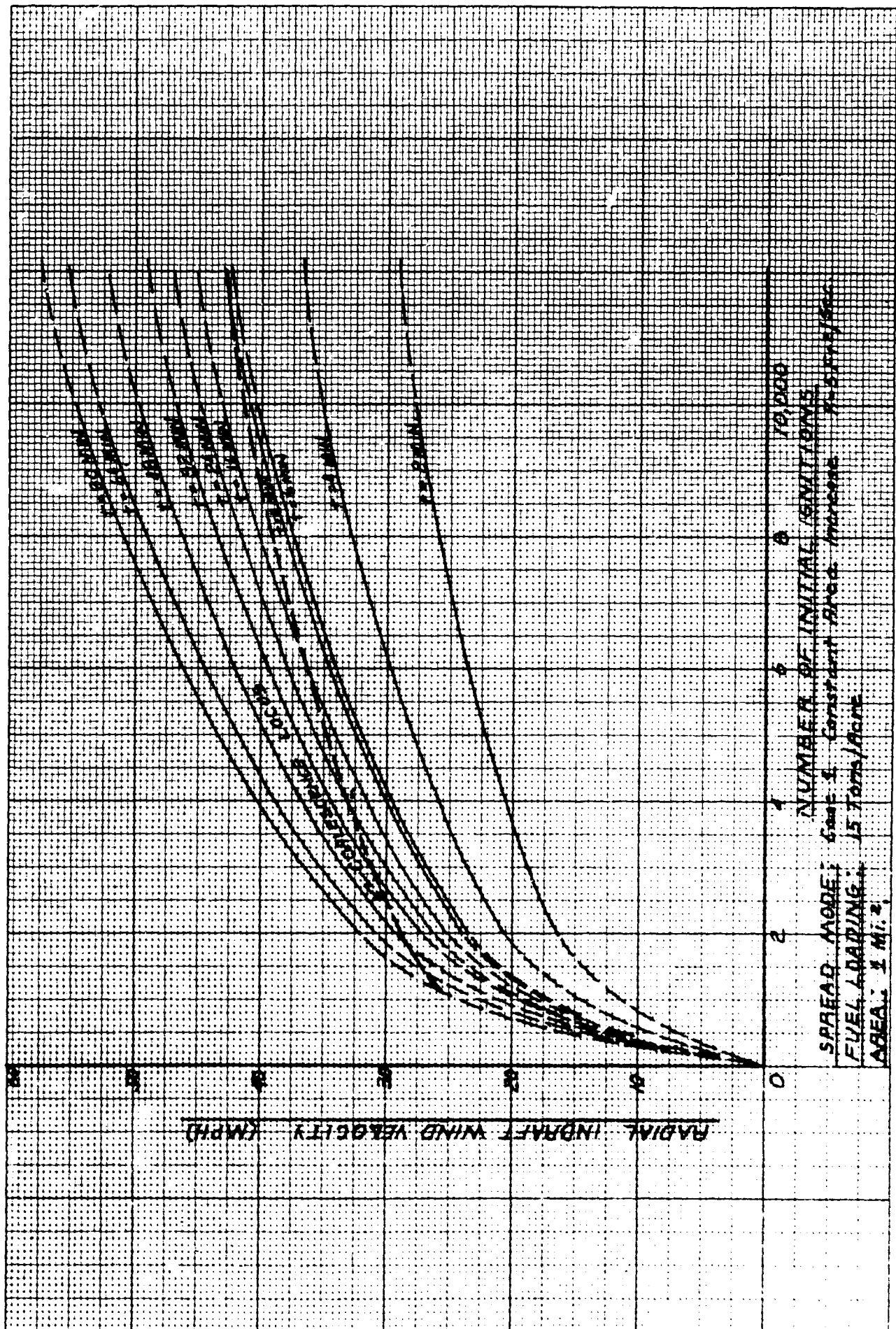


Fig. IV-6

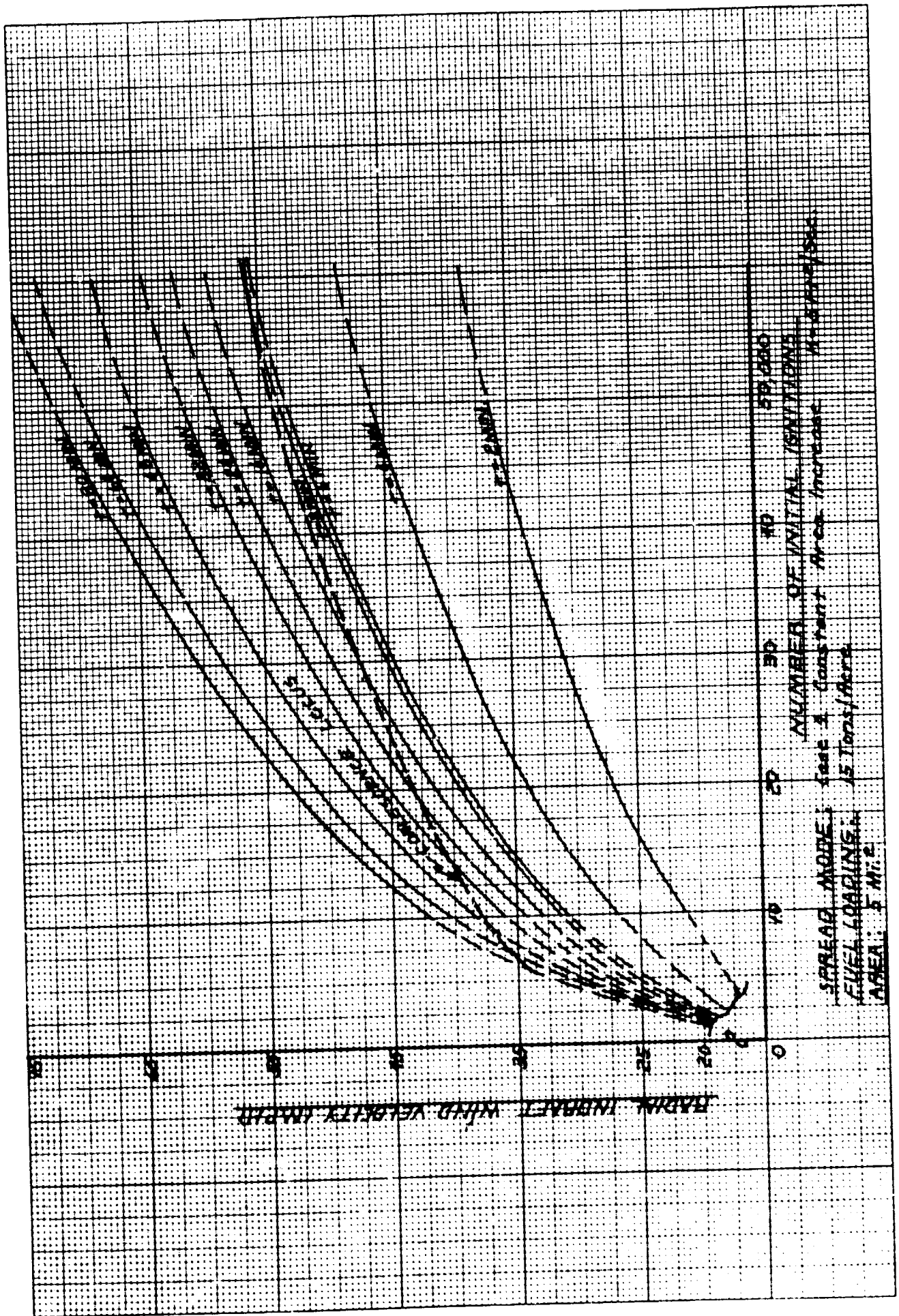


Fig. IV-7



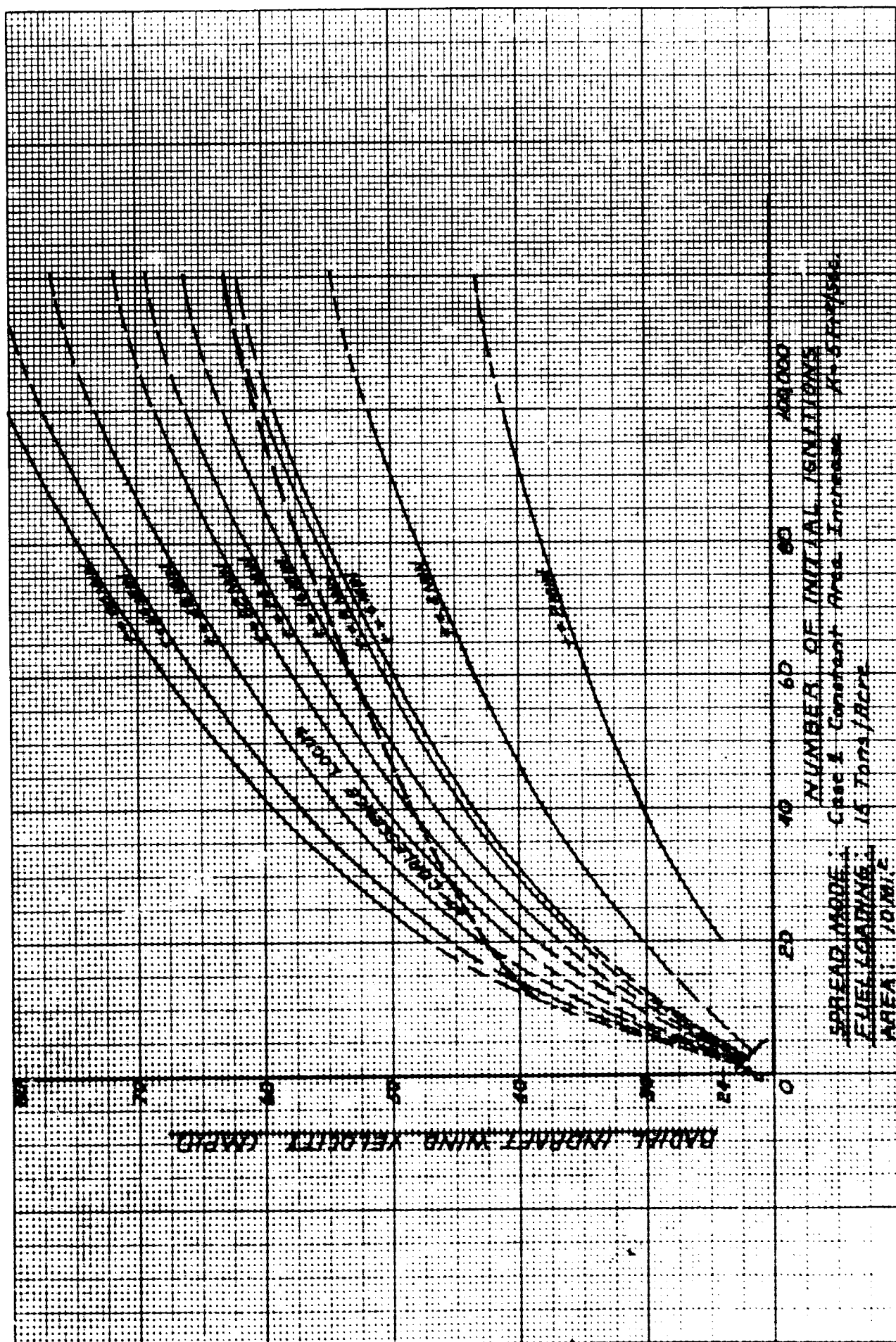


Fig. IV-8



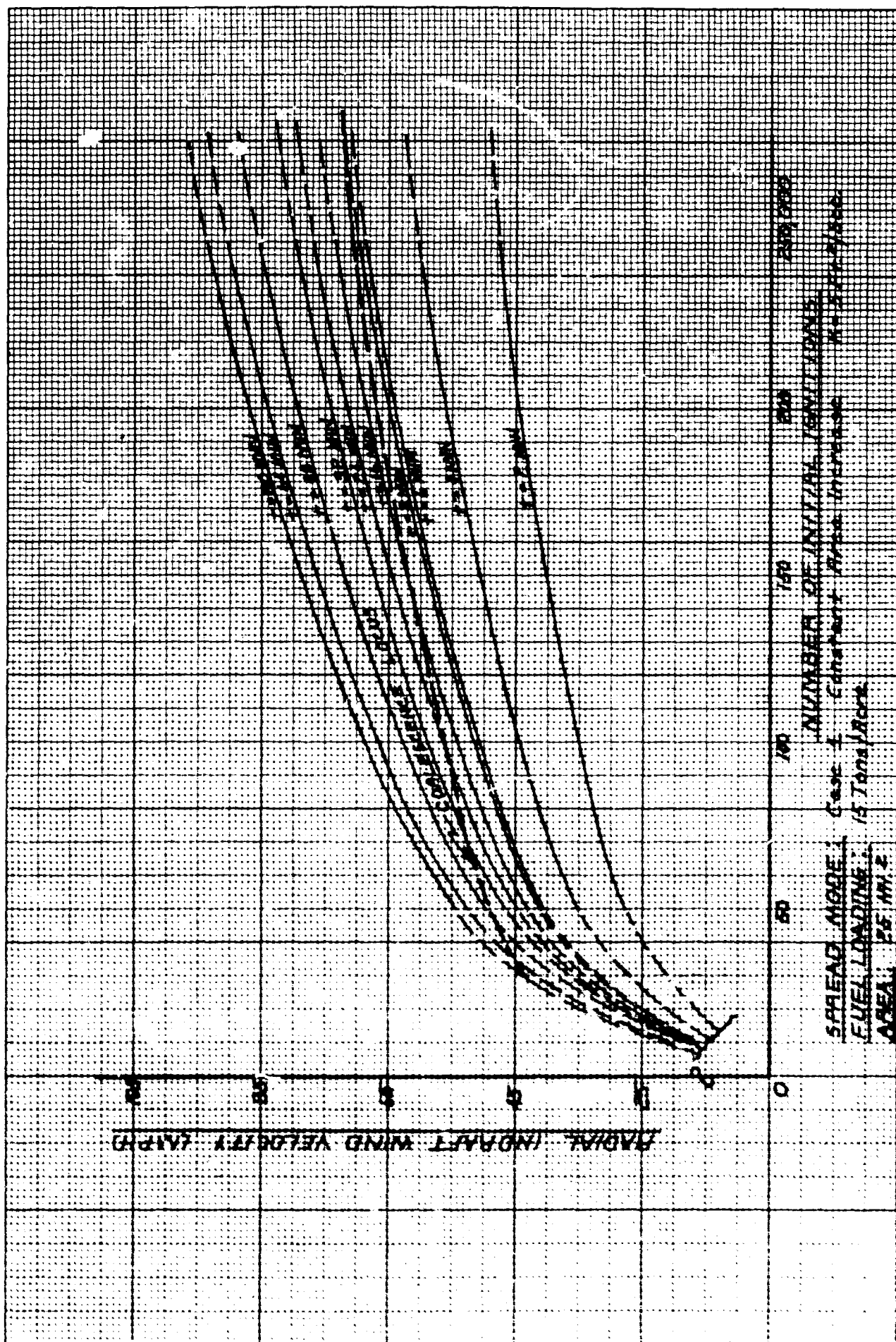


Fig. IV-10

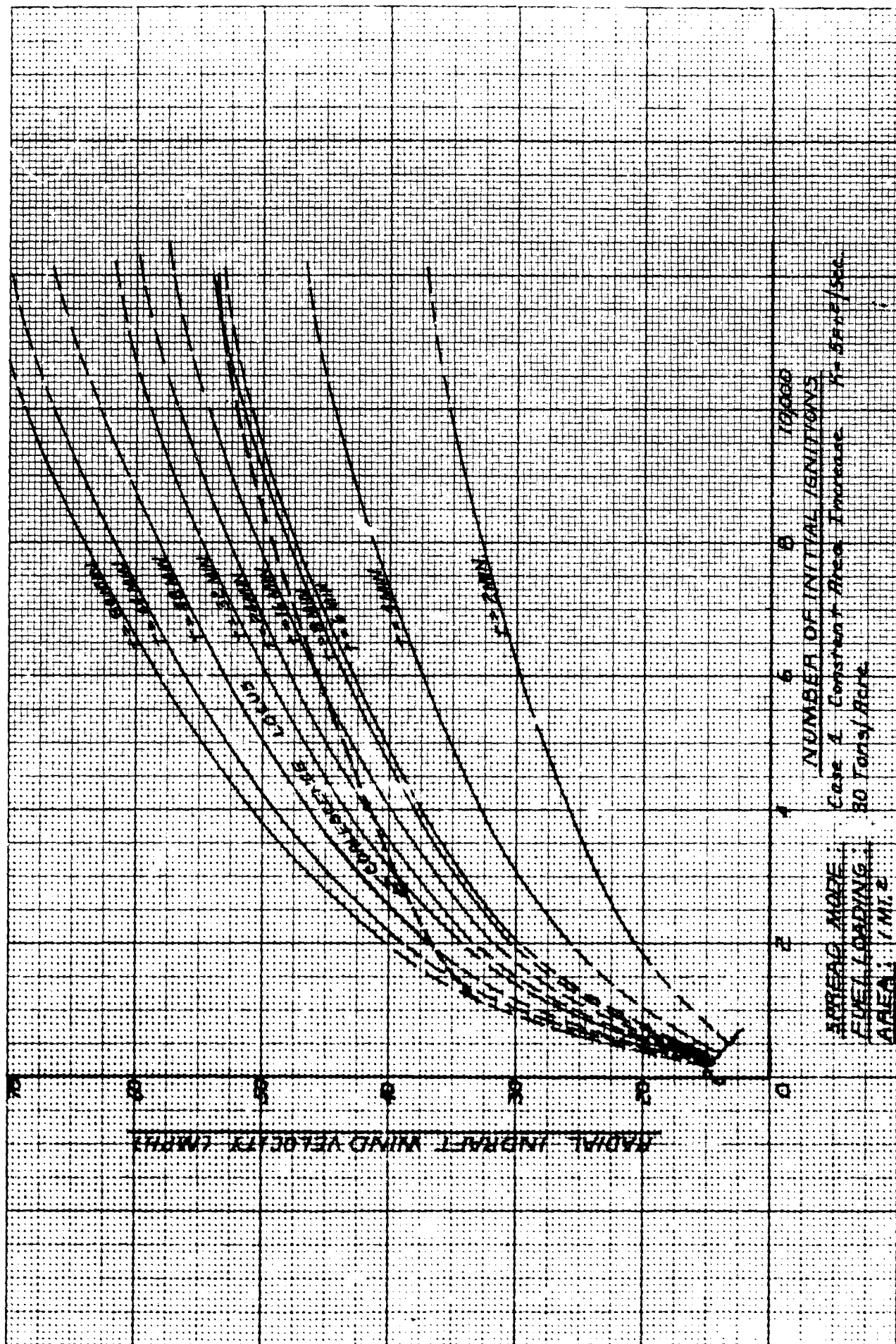


Fig. IV-11



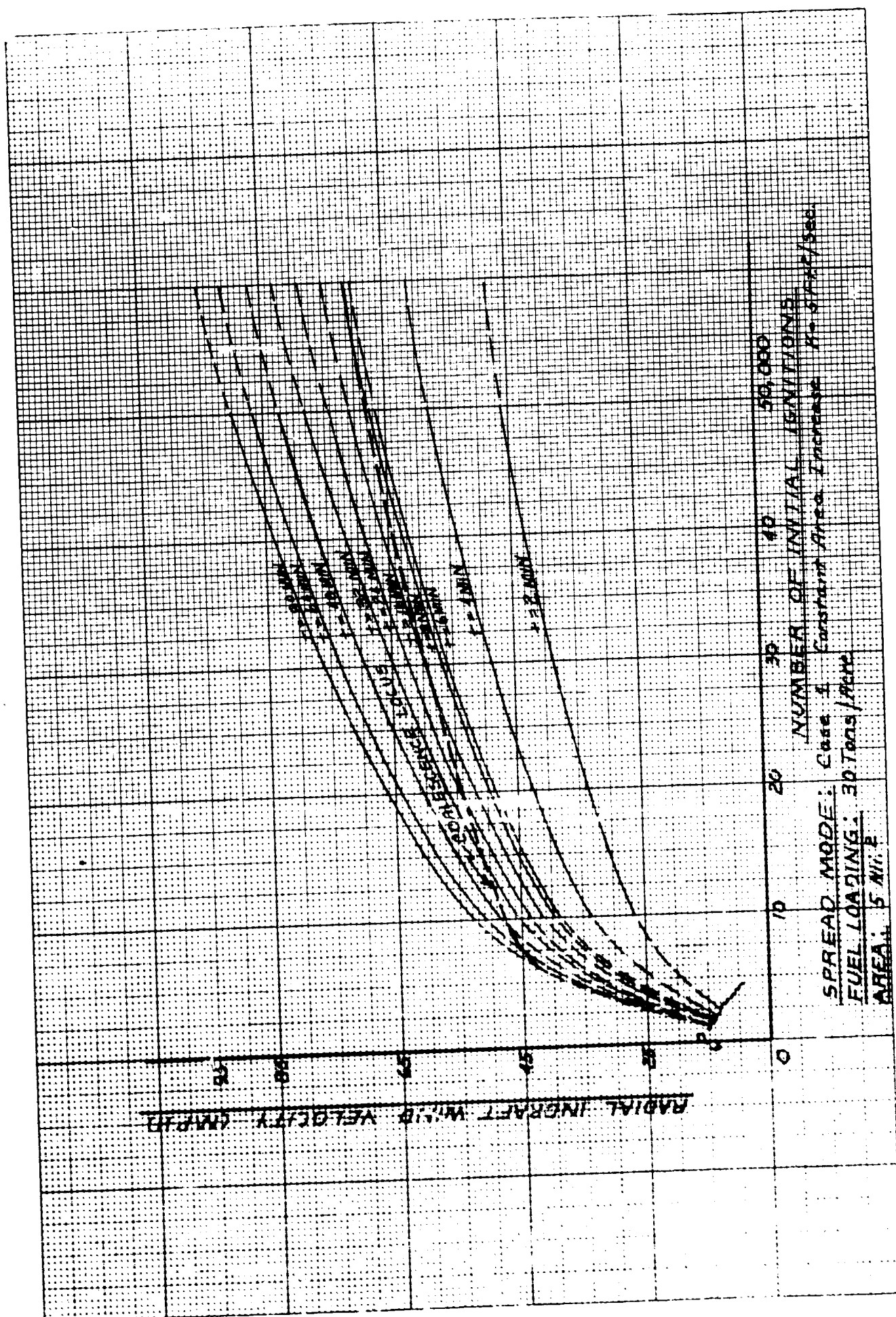


Fig. IV-12

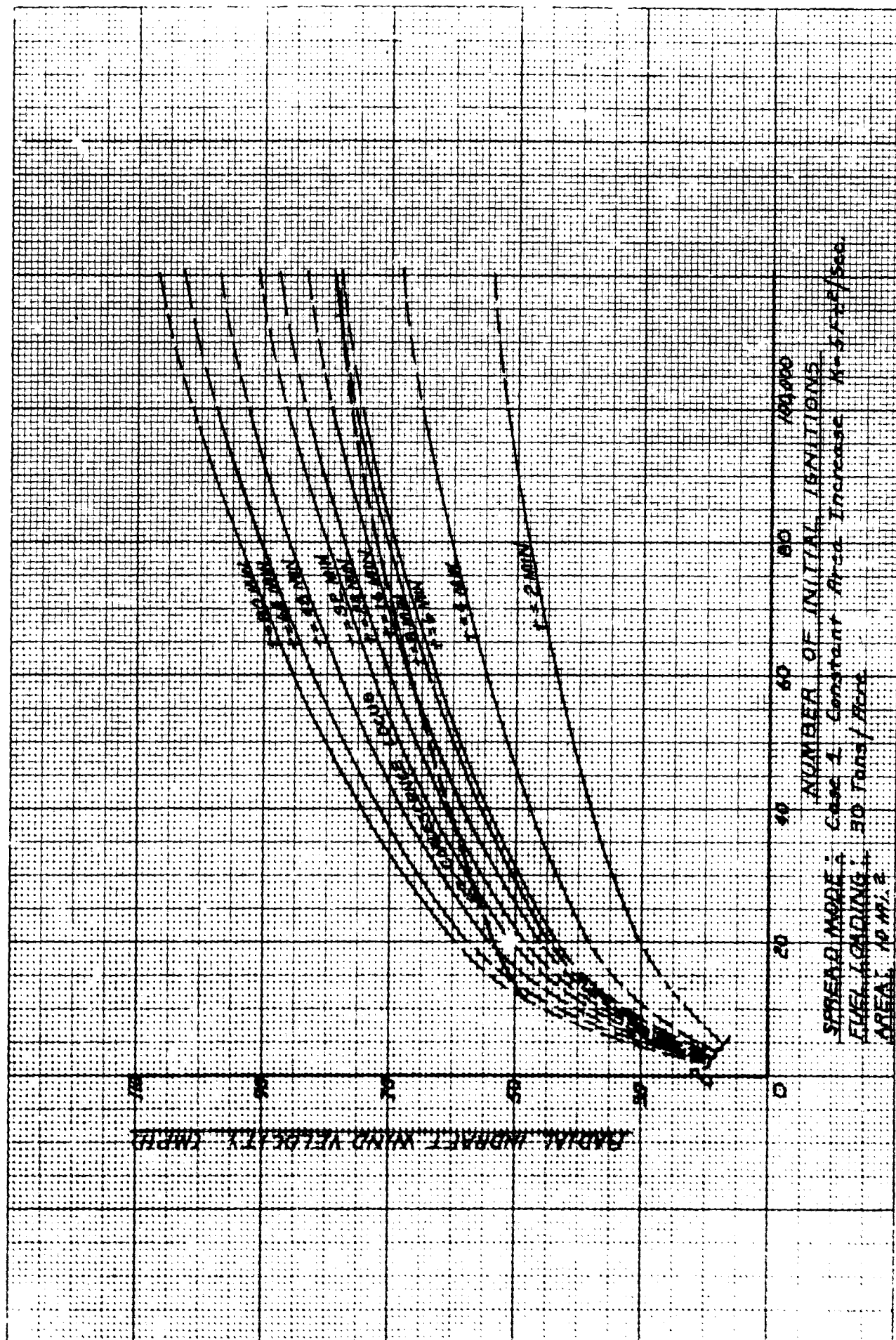


Fig. IV-13

FREDERICK POST COMPANY  
30 LTRIC CROSS SECTION 20 X 20 PER INCH

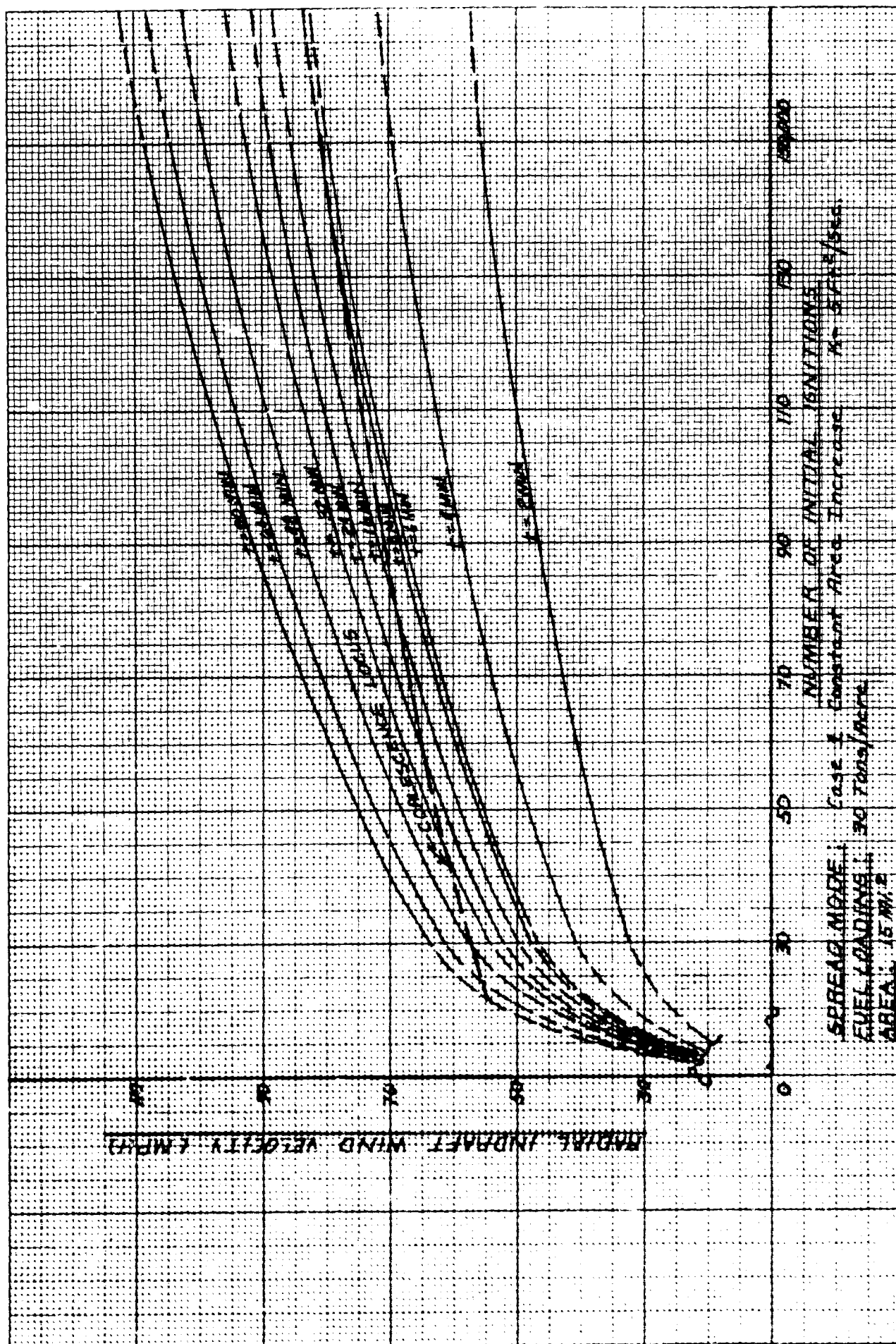


Fig. IV-14

FREDERICK POST COMPANY  
 101115 CROSS SECTION 2 4.20 PER INCH

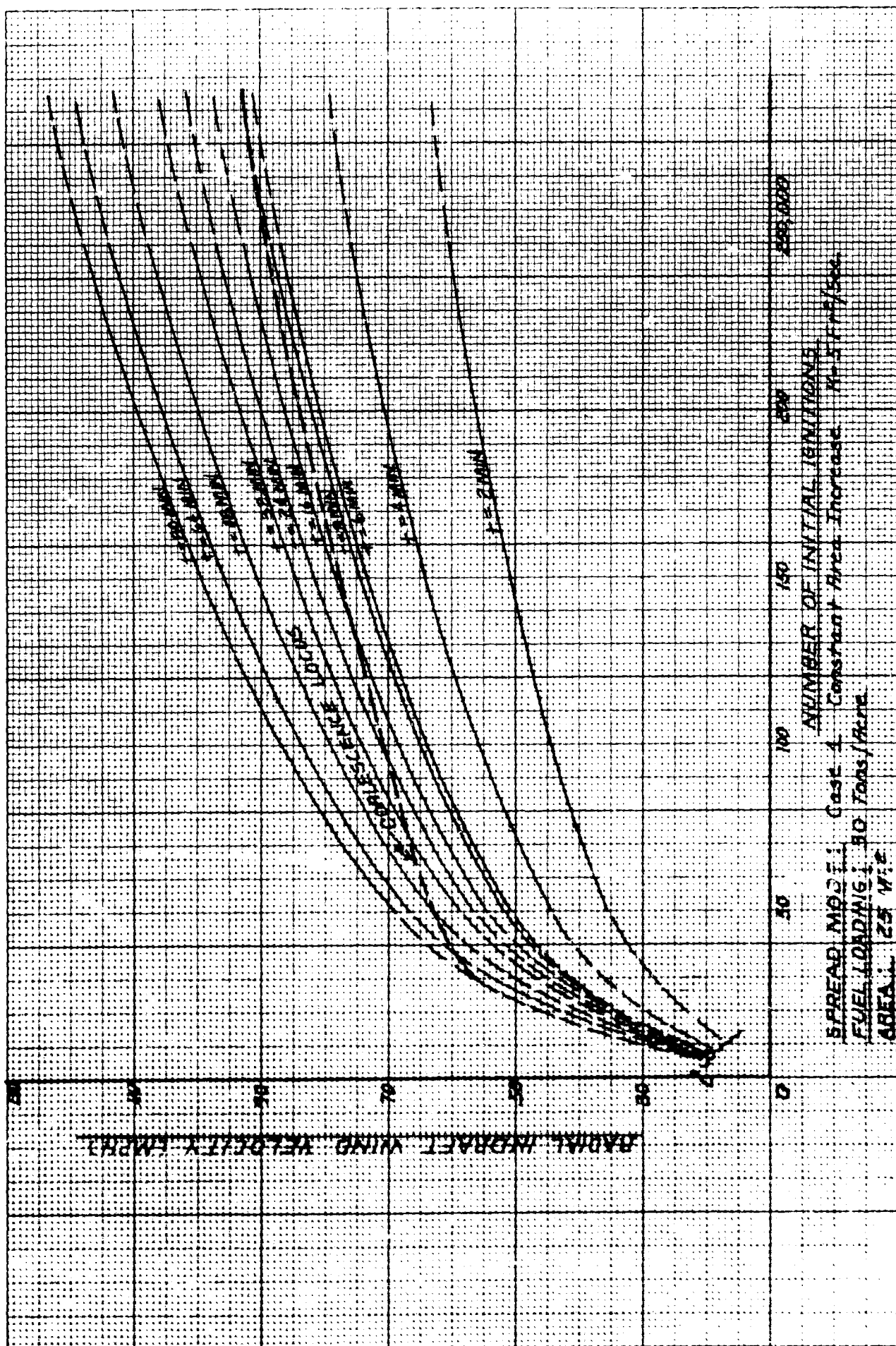


Fig. IV-15



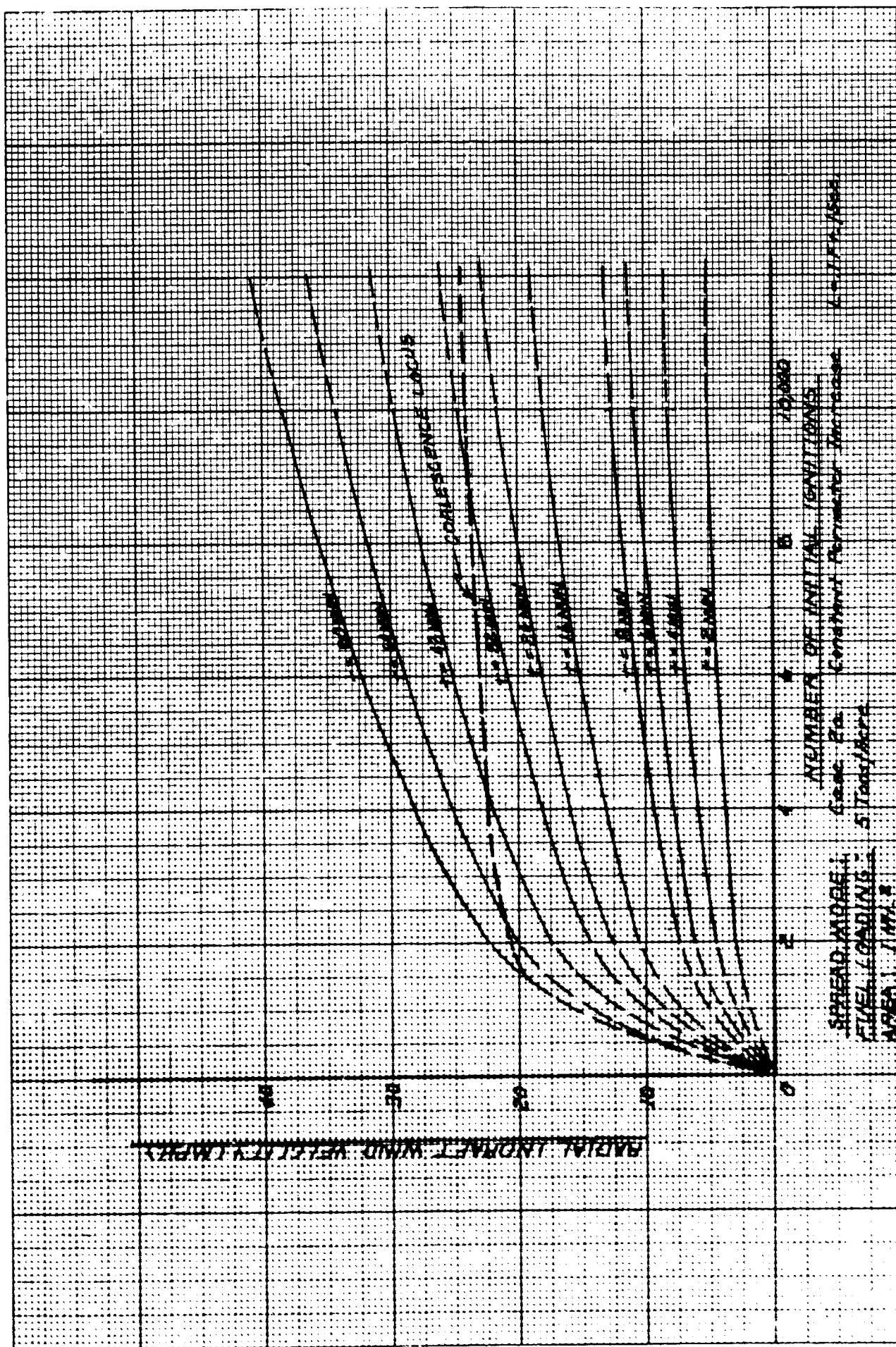


Fig. IV-16

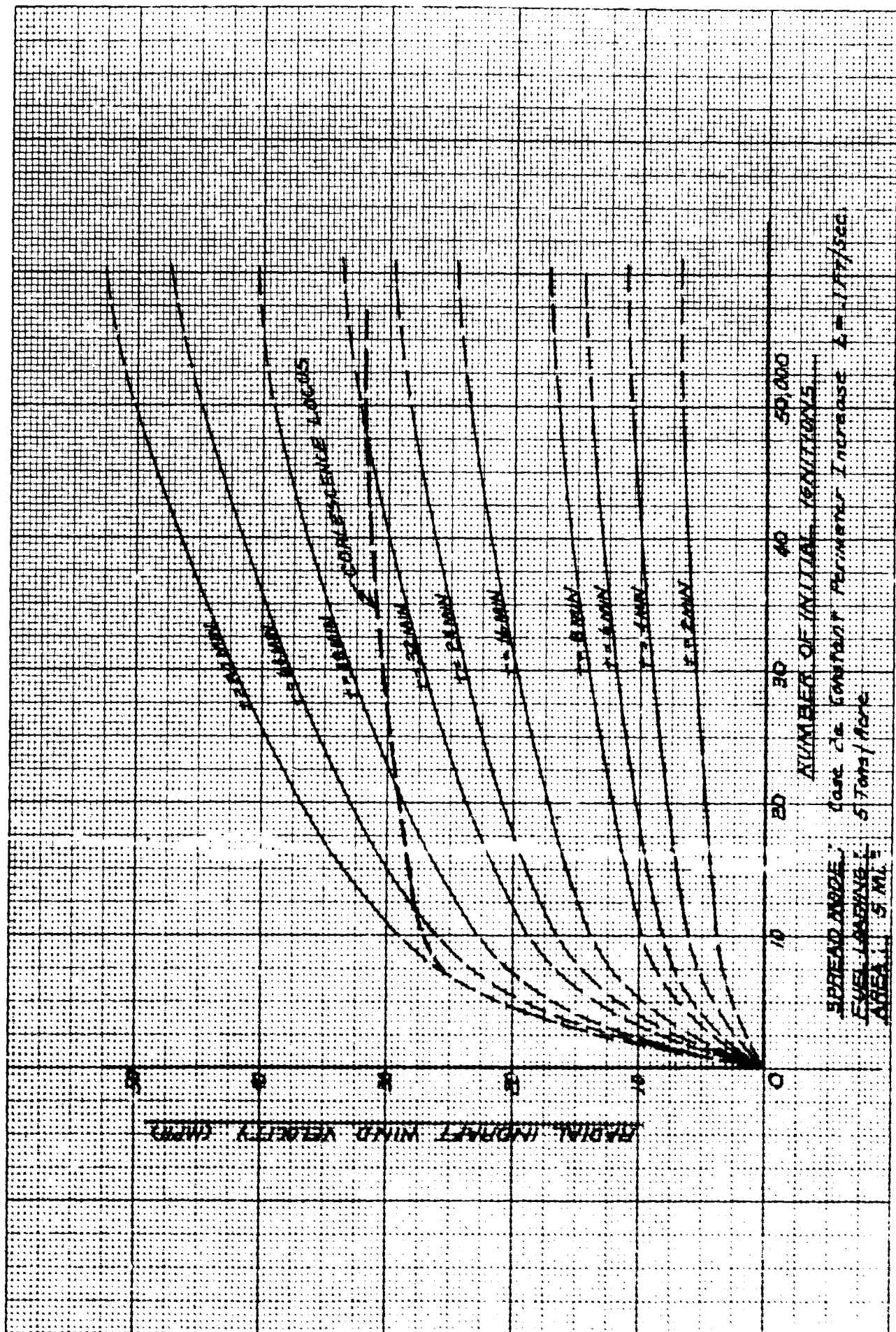


Fig. IV-17

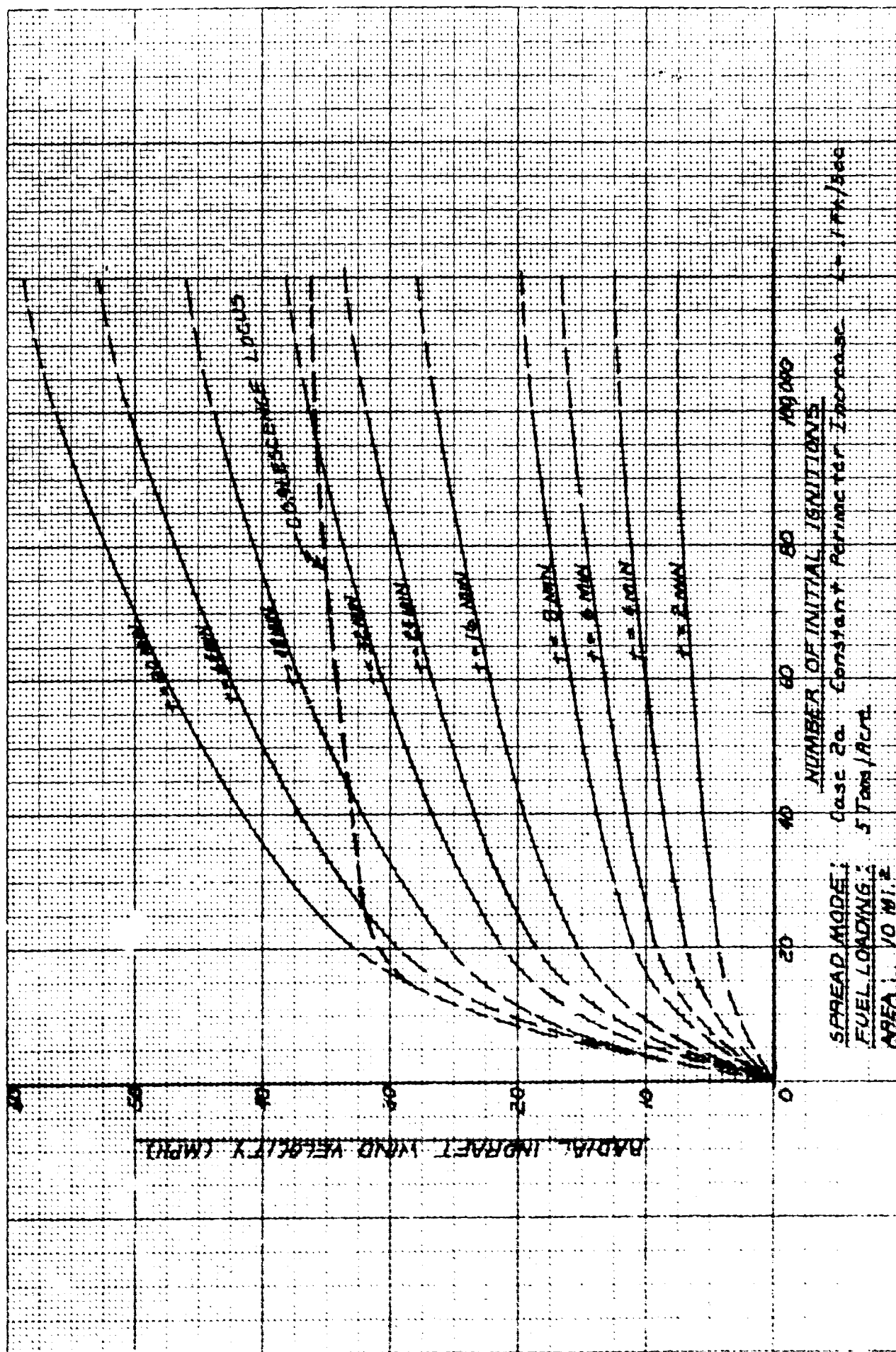


Fig. IV-18

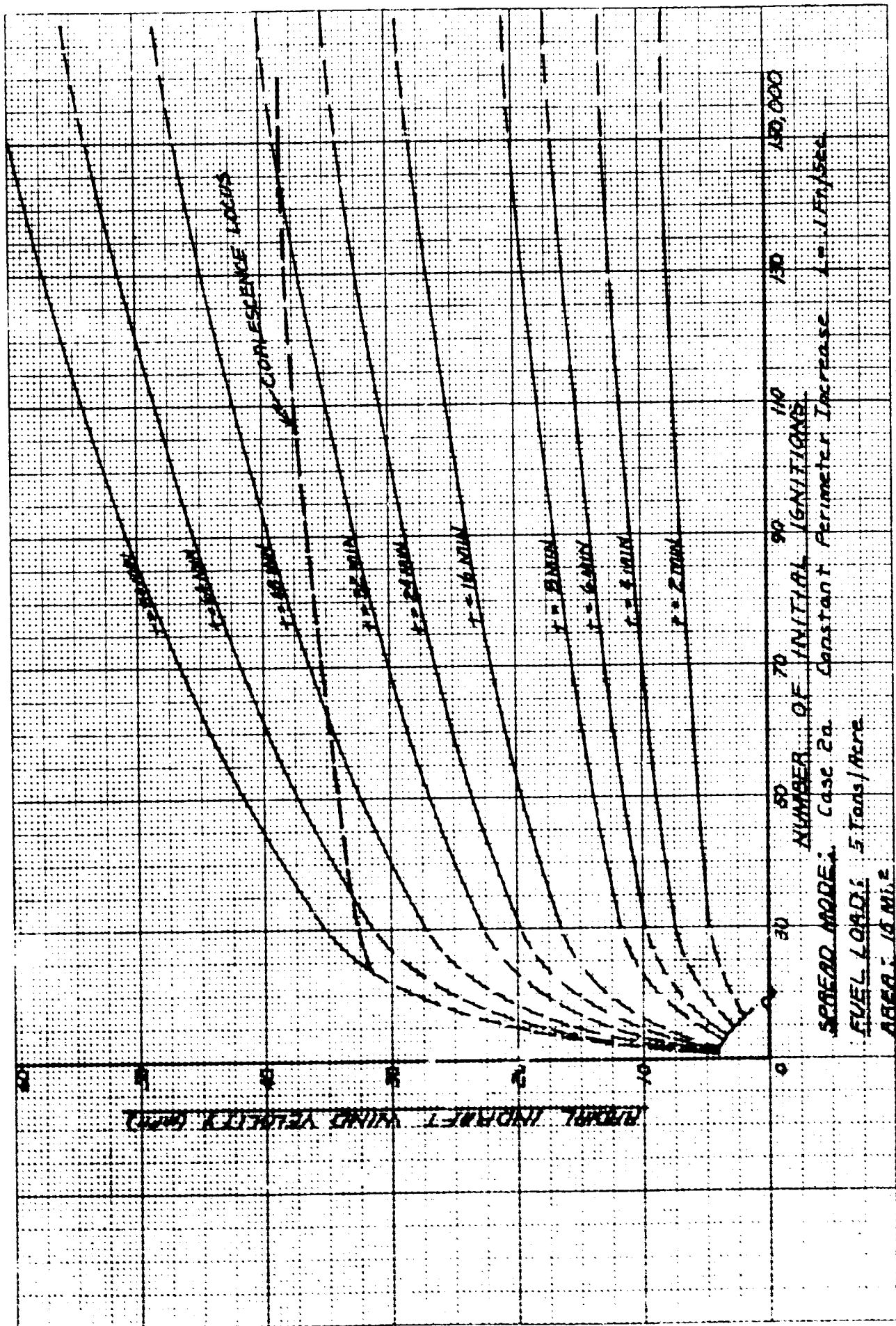


Fig. IV-19



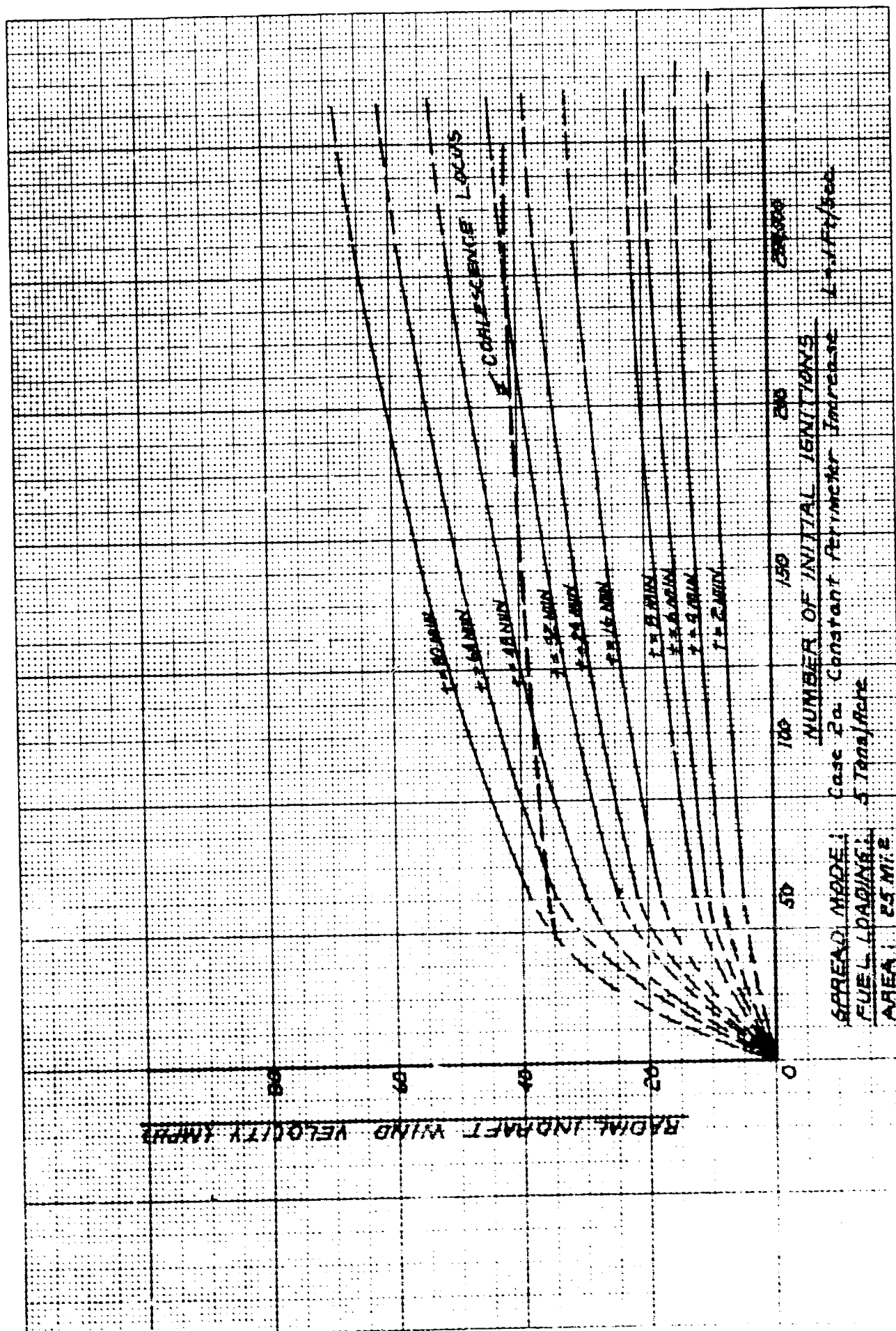


Fig. IV-20

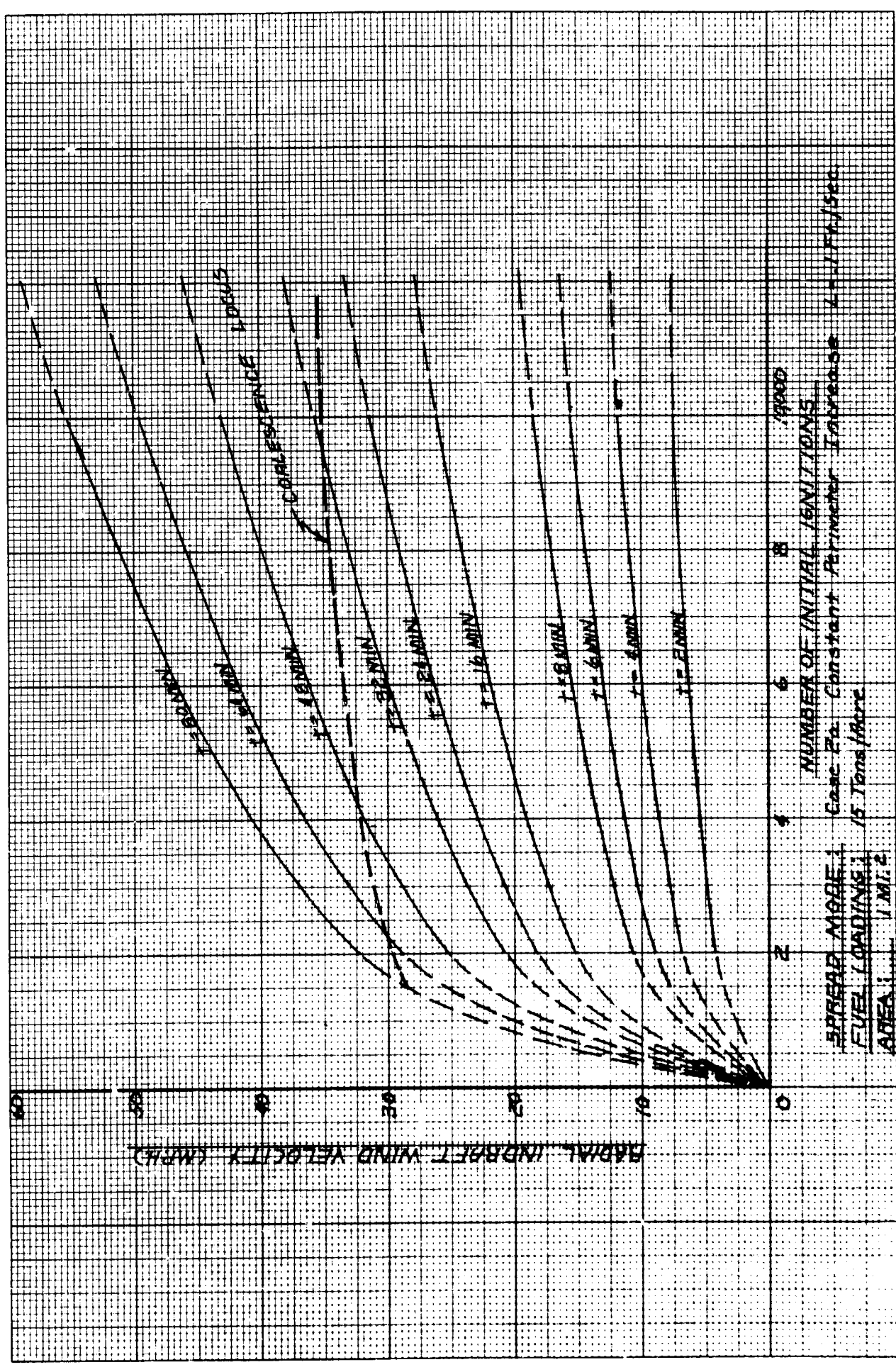


Fig. IV-21

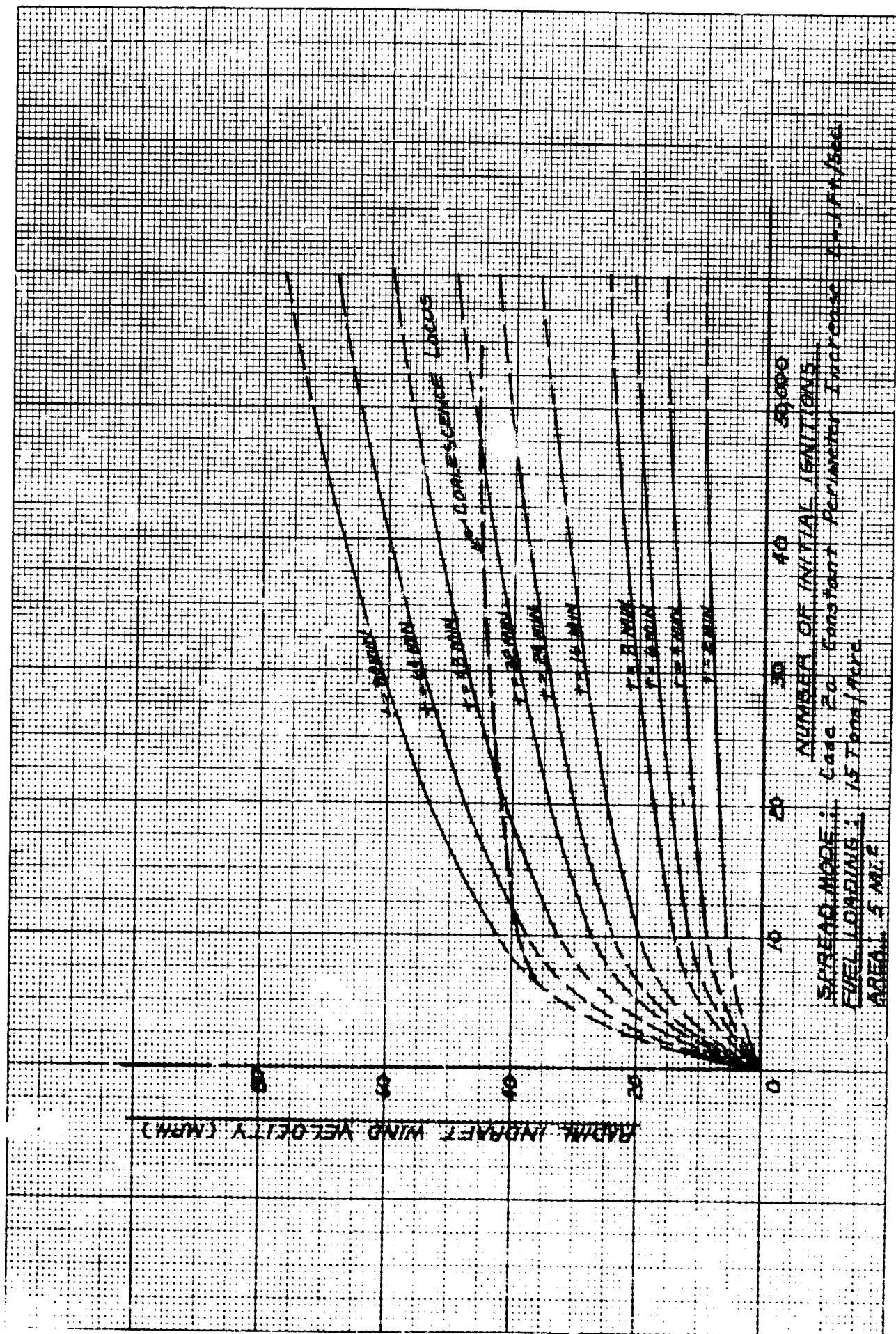


Fig. IV-22





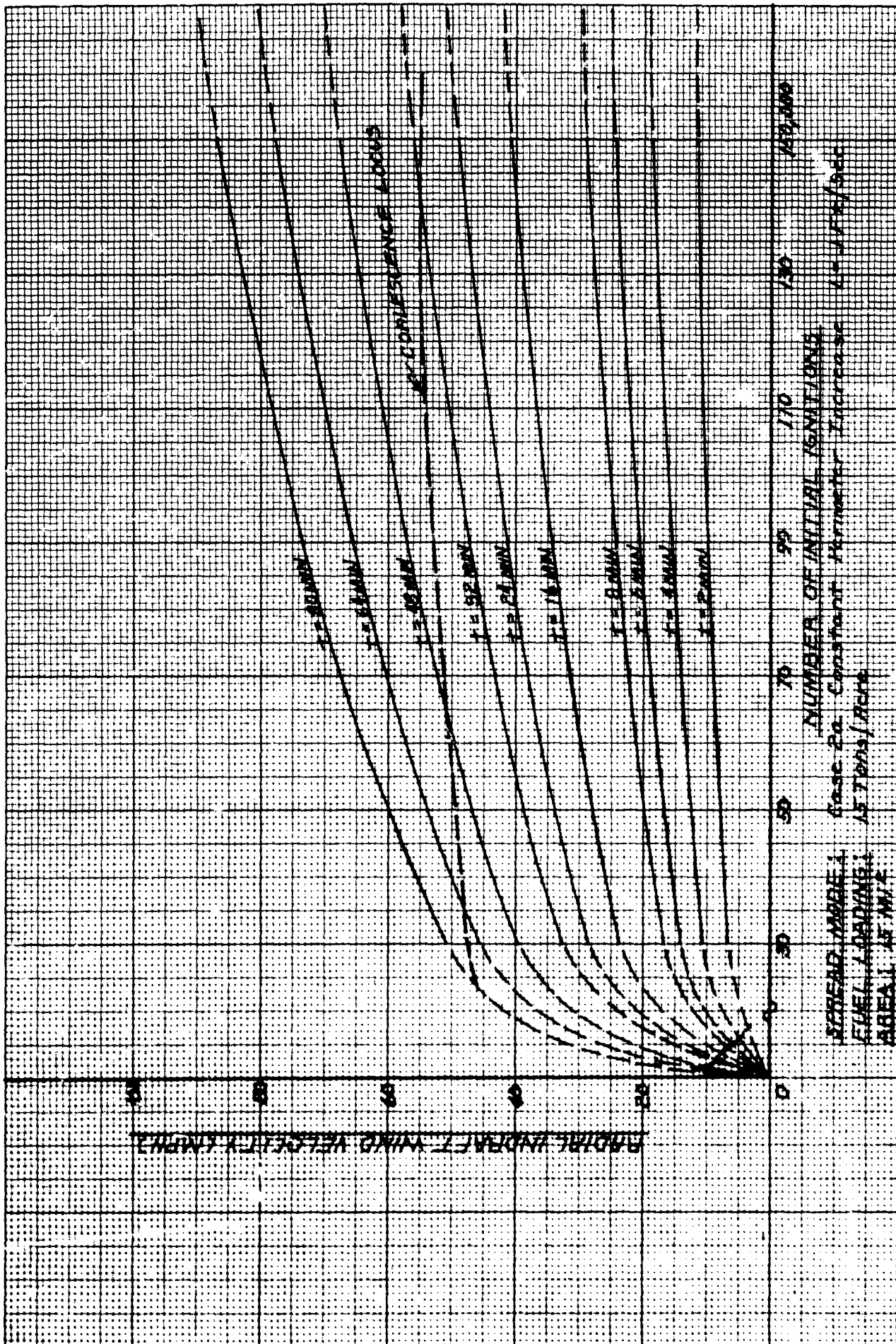


Fig. IV-24

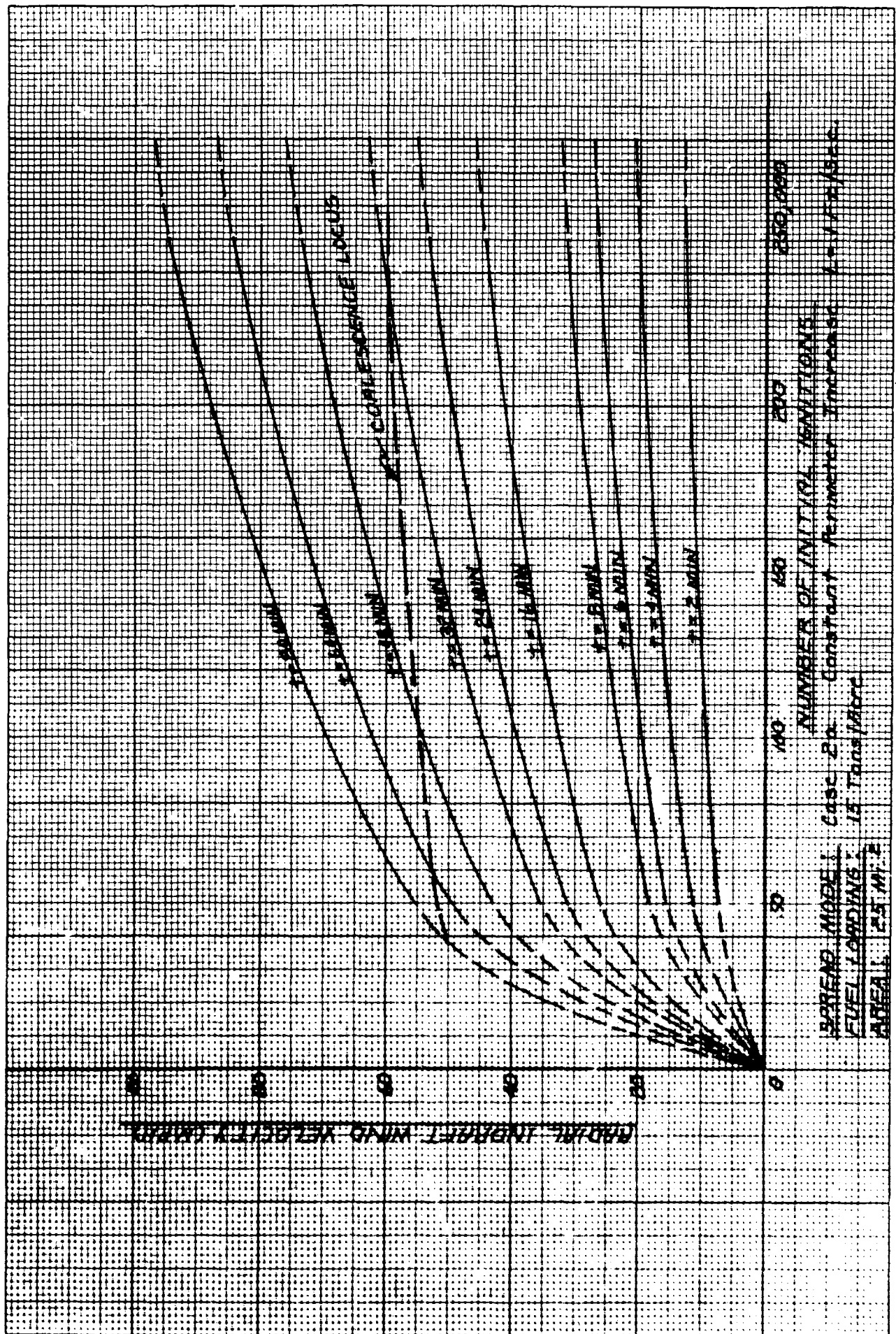


Fig. IV-25

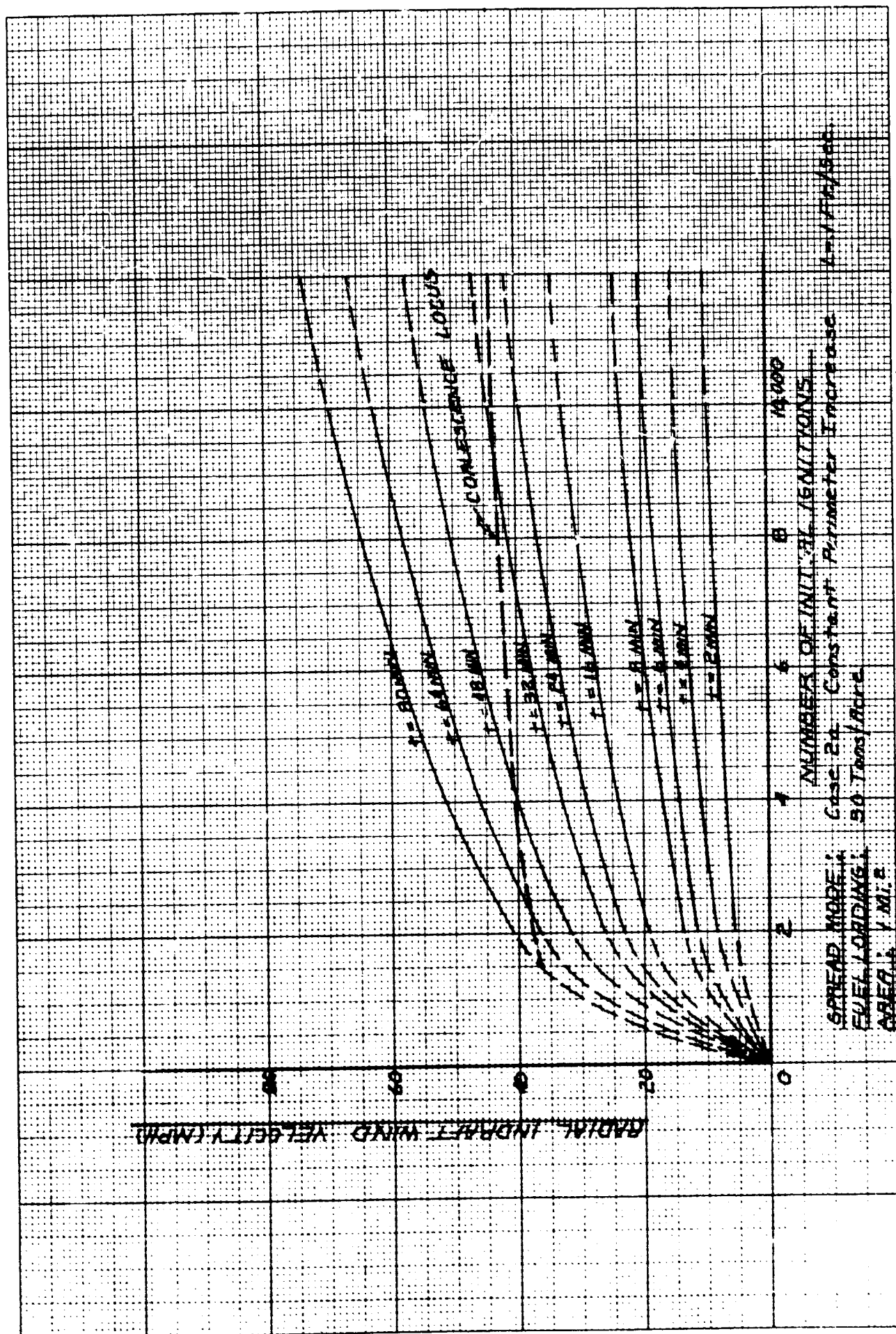


Fig. IV-26

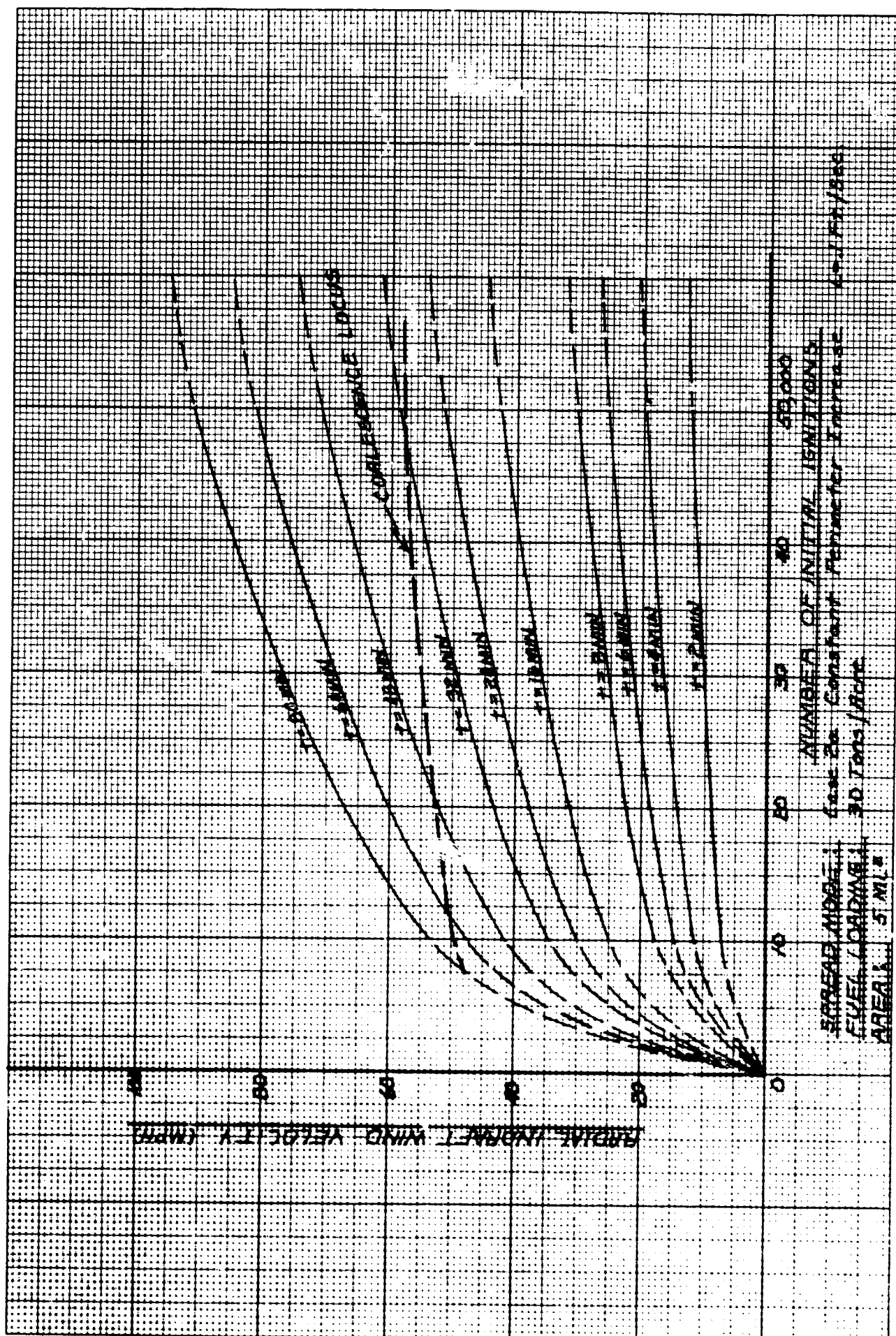
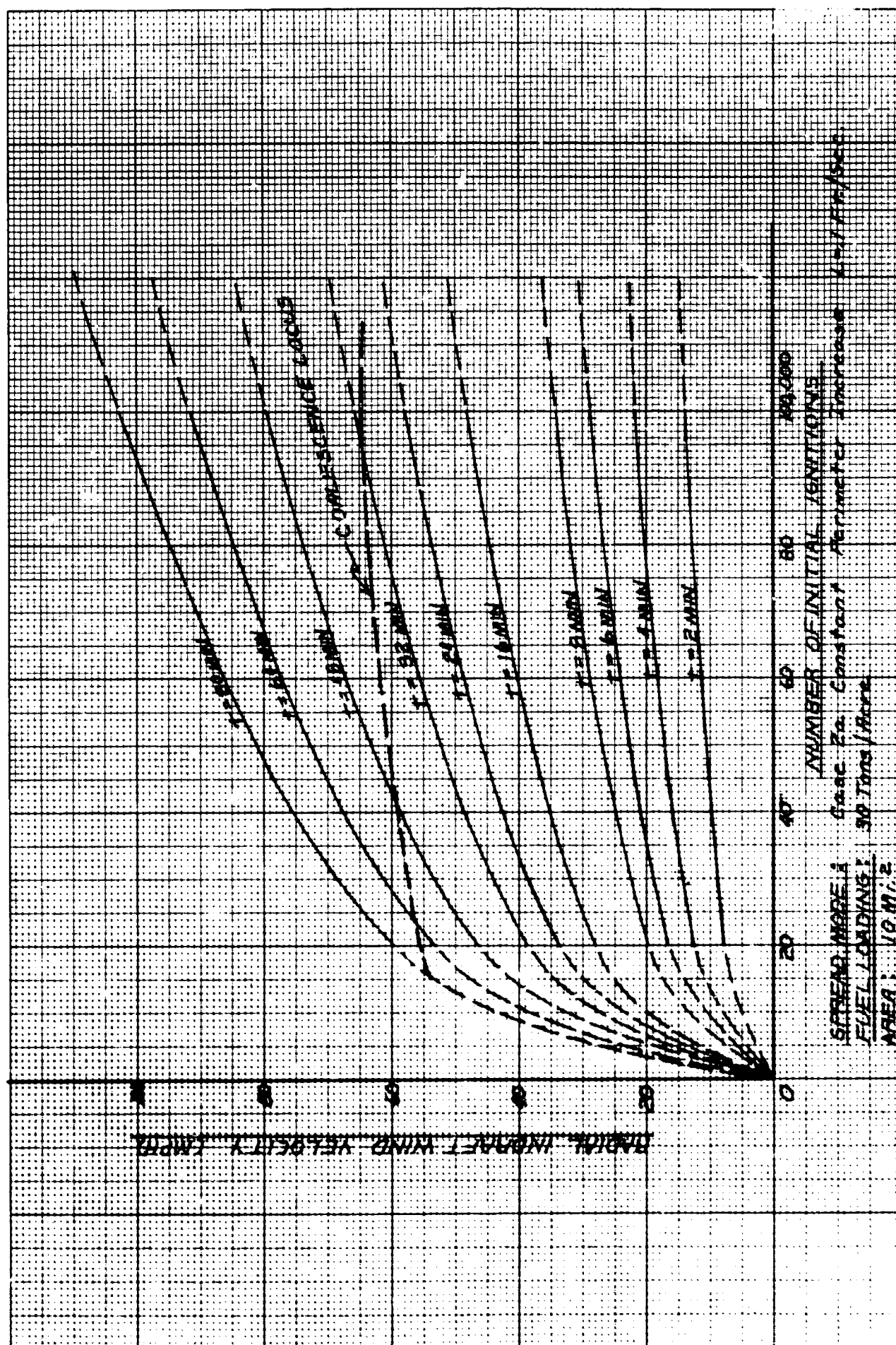


Fig. IV-27





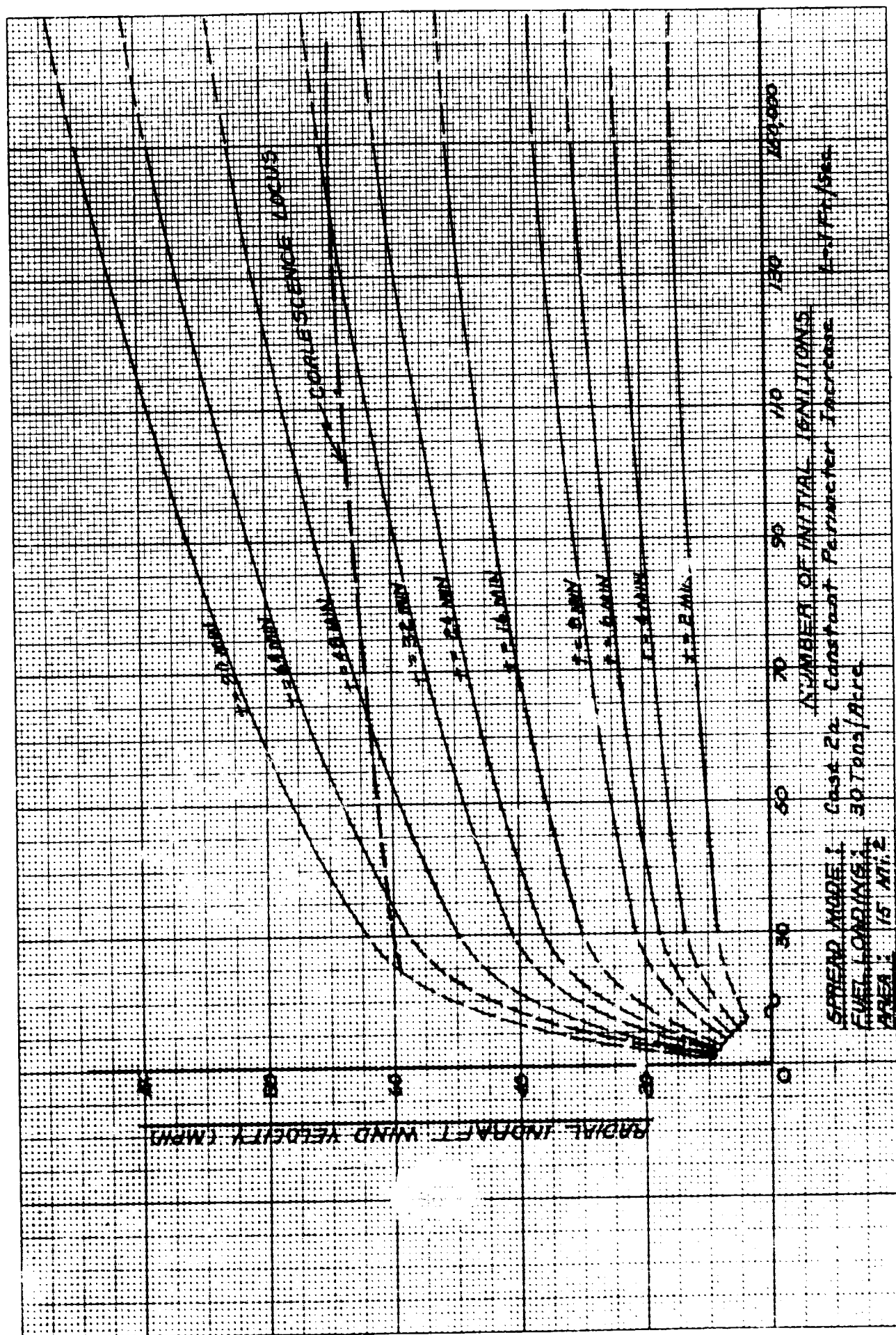


Fig. IV-29

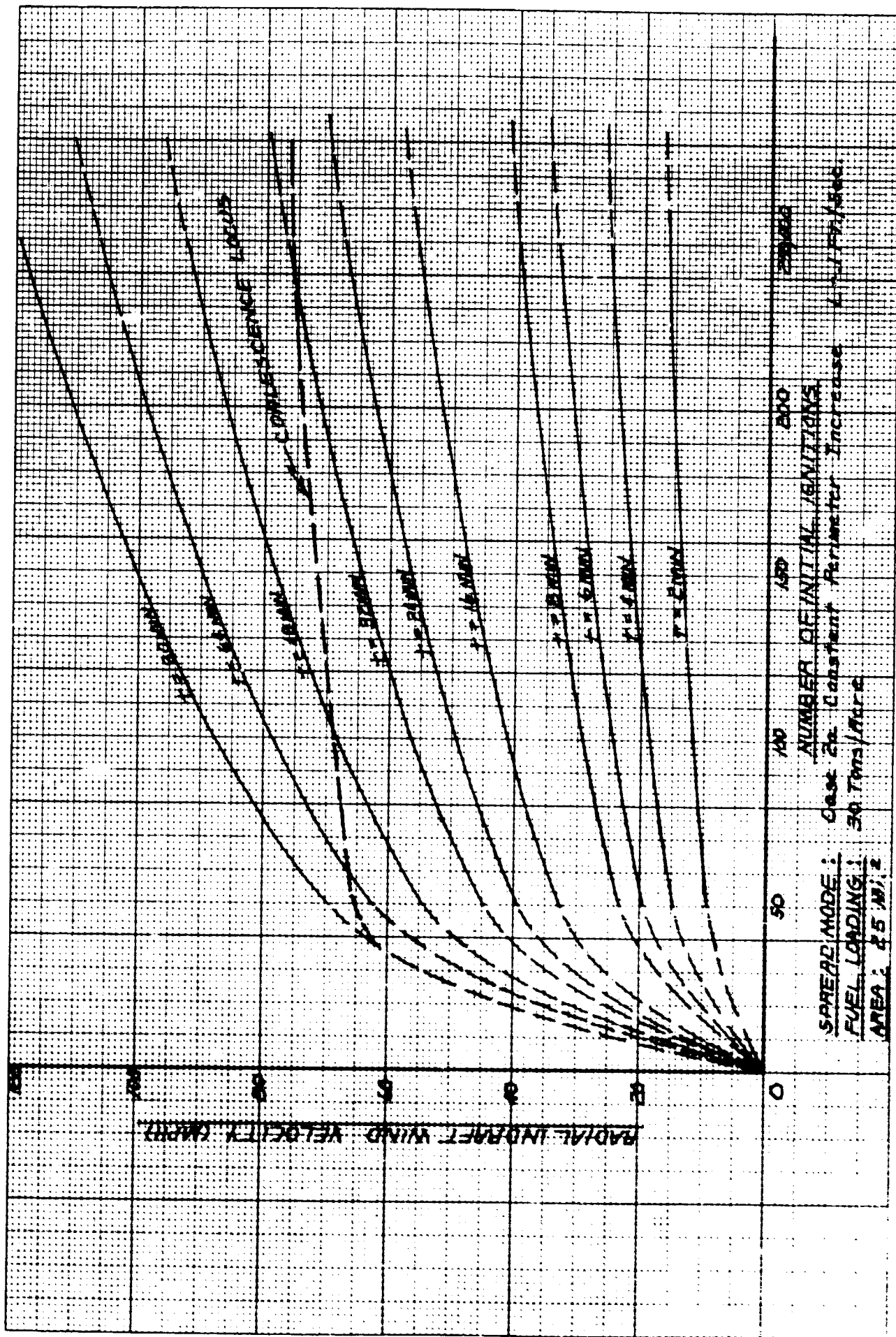


Fig. IV-30

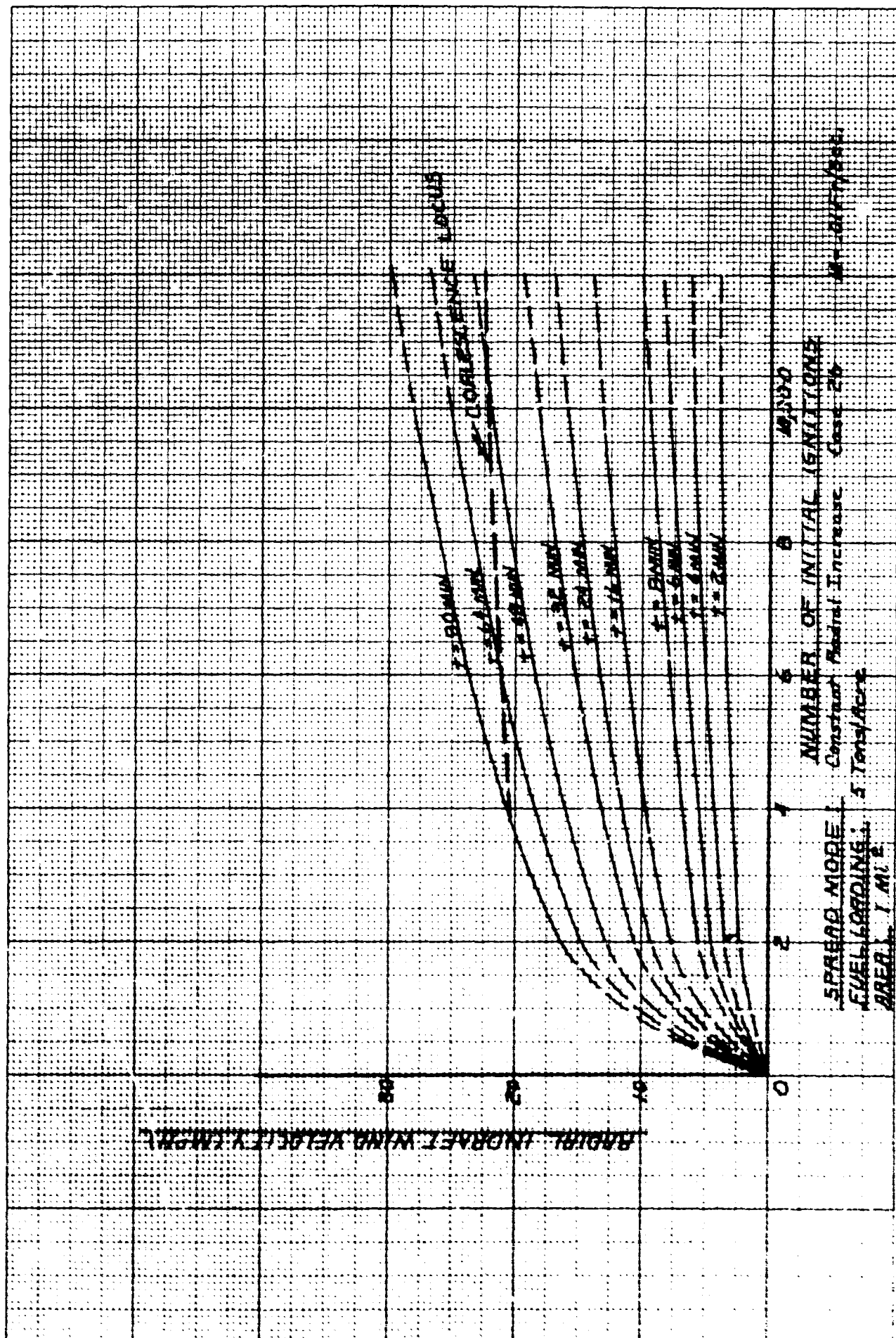


Fig. IV-31



Fig. IV-32



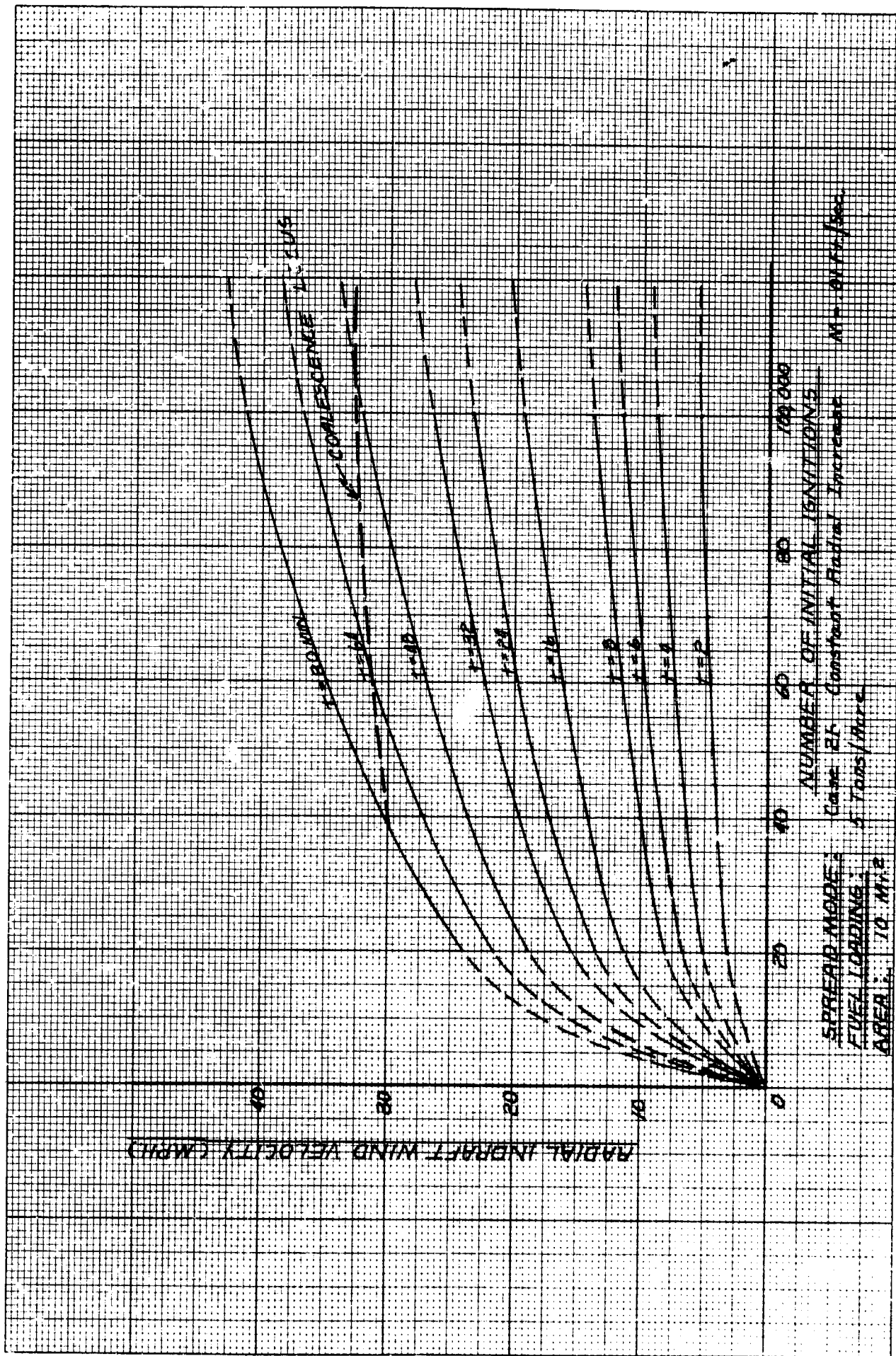


Fig. IV-33

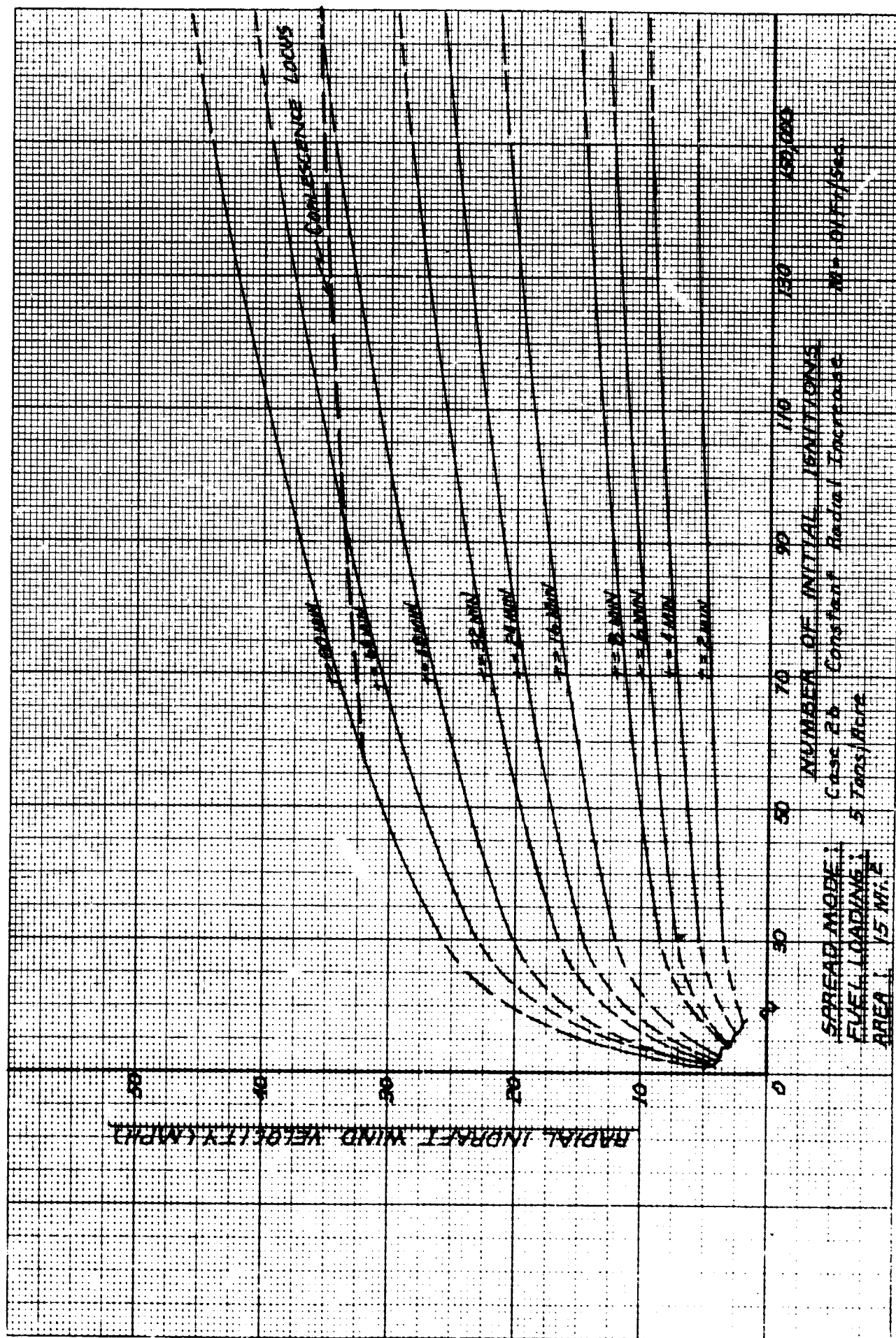


Fig. IV-34

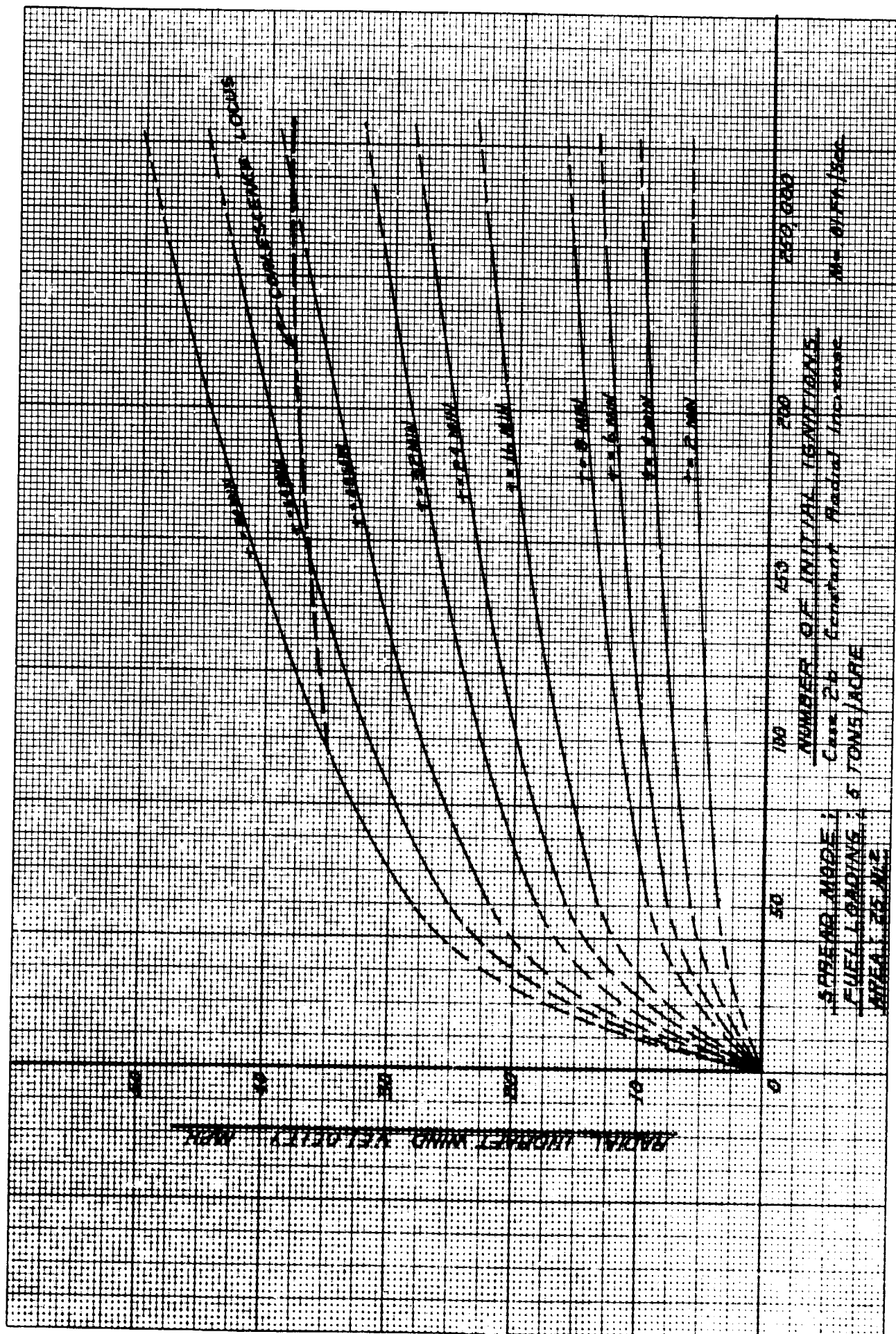


Fig. IV-35



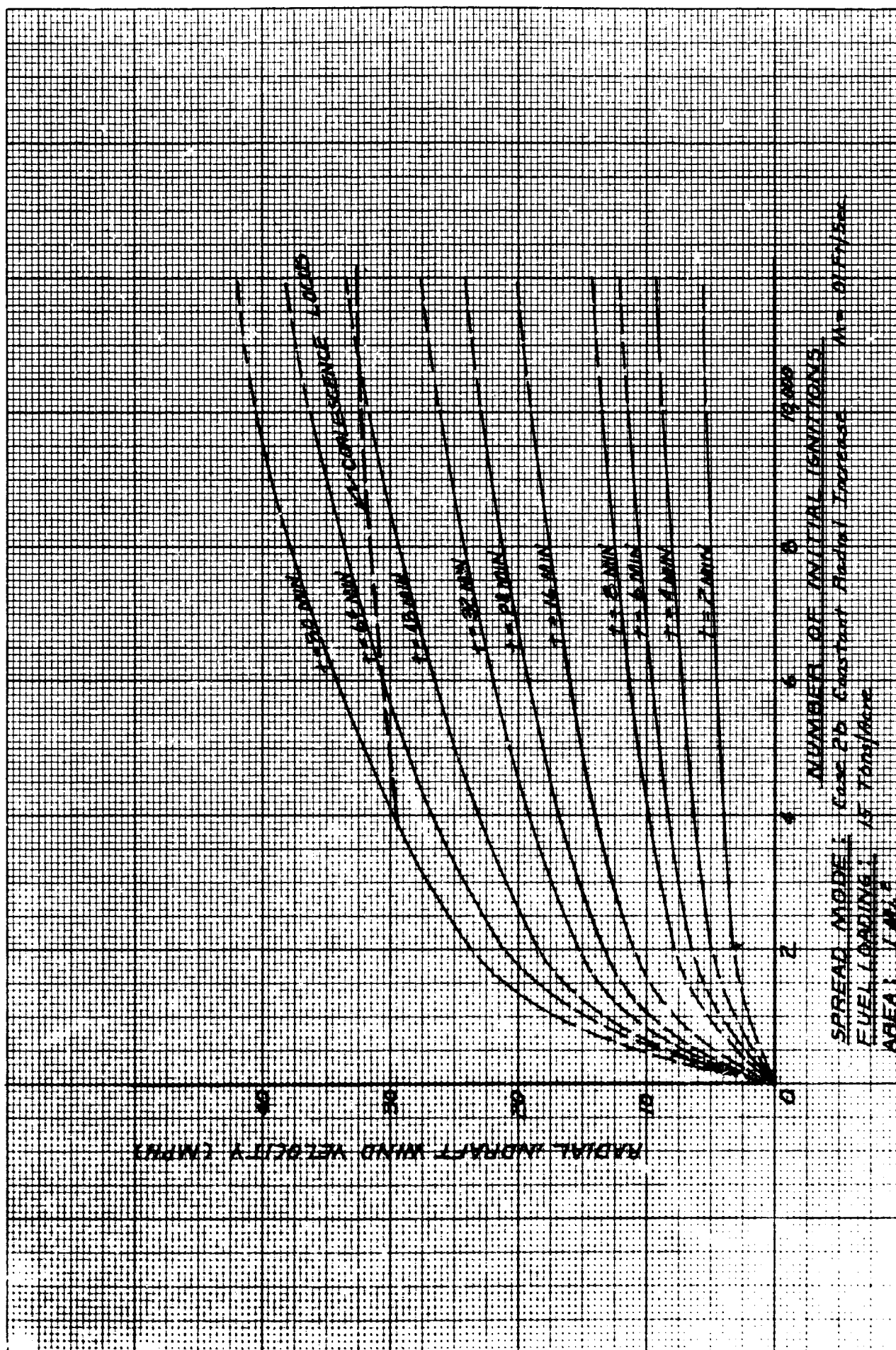


Fig. IV-36

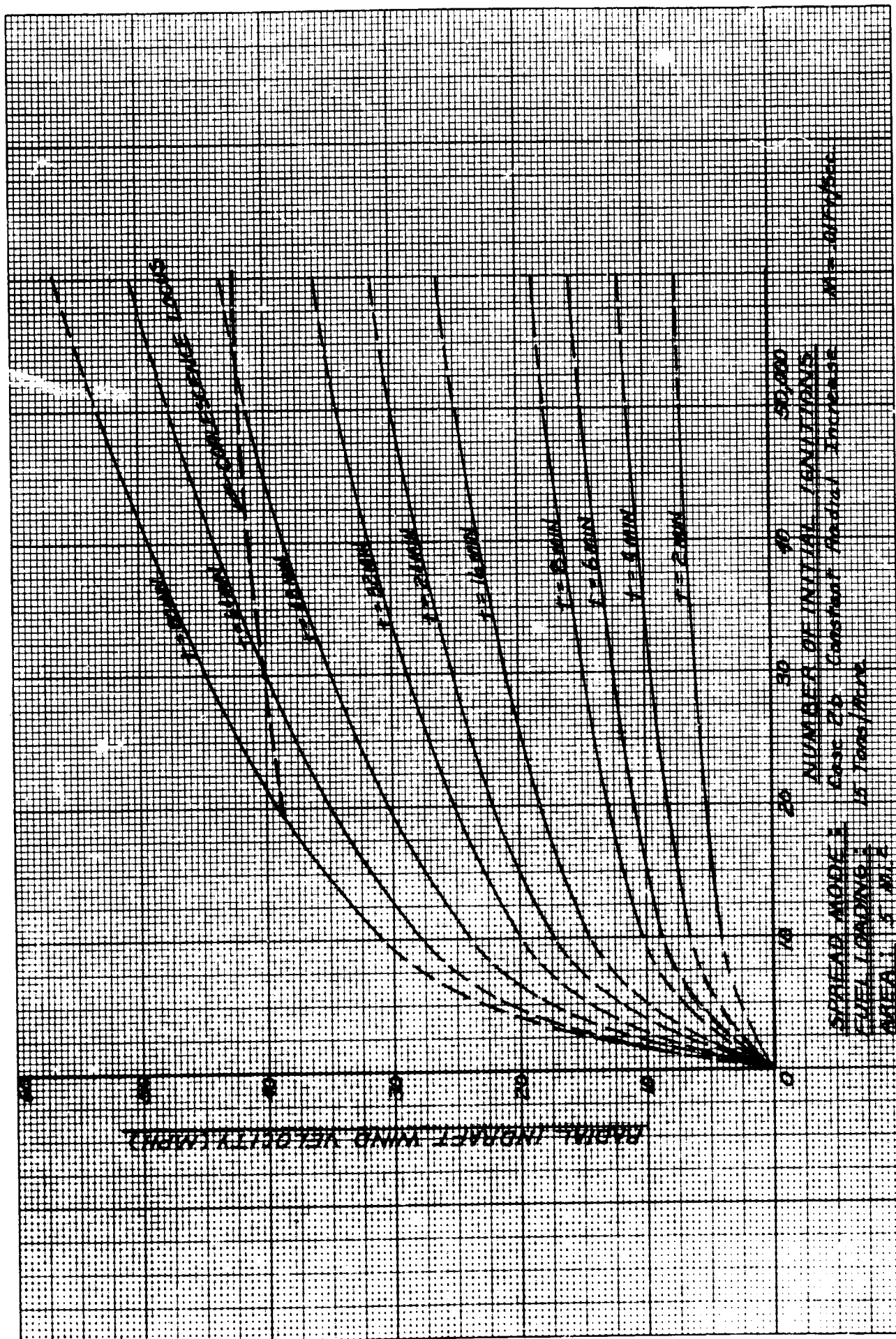


Fig. IV-37

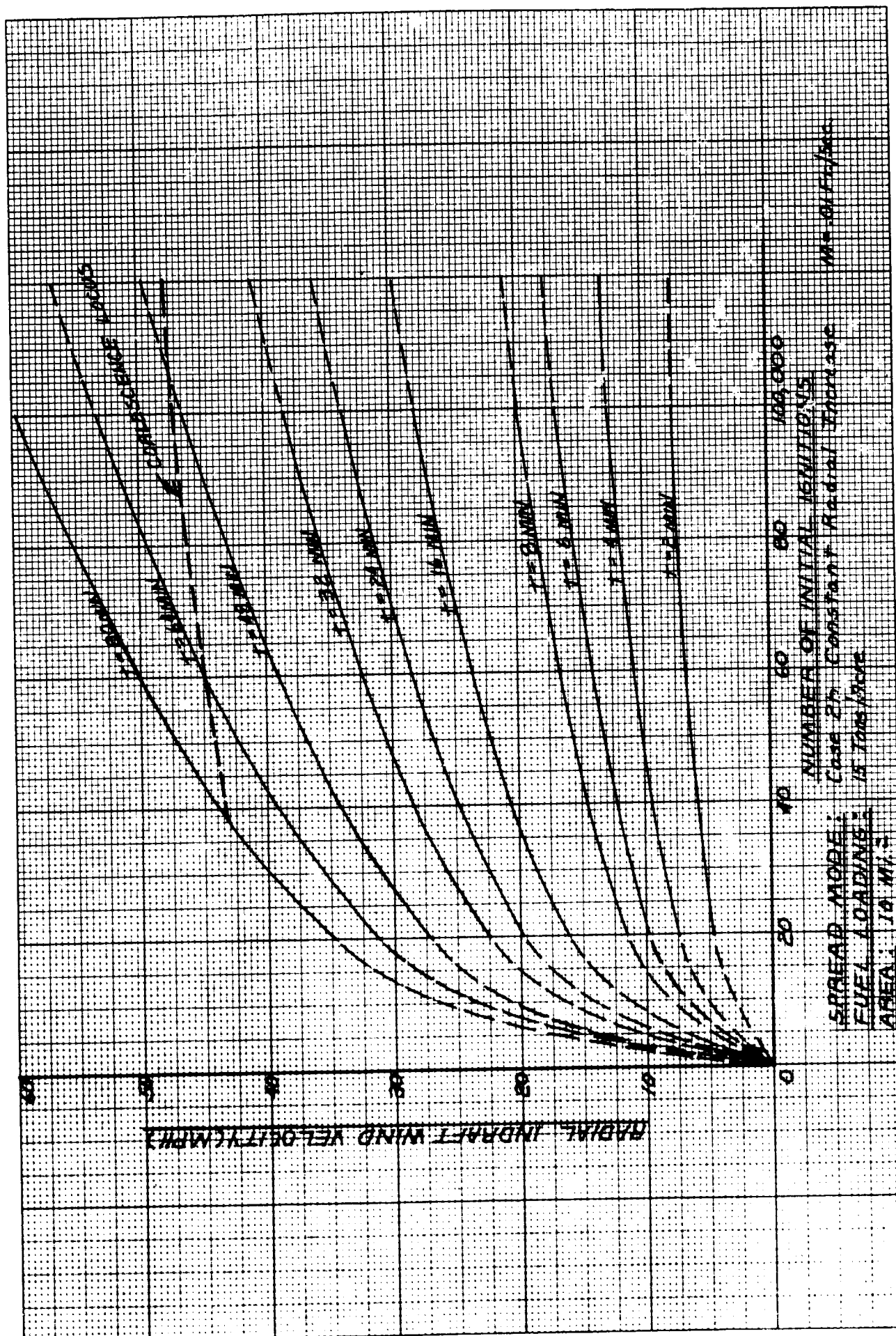


Fig. IV-38

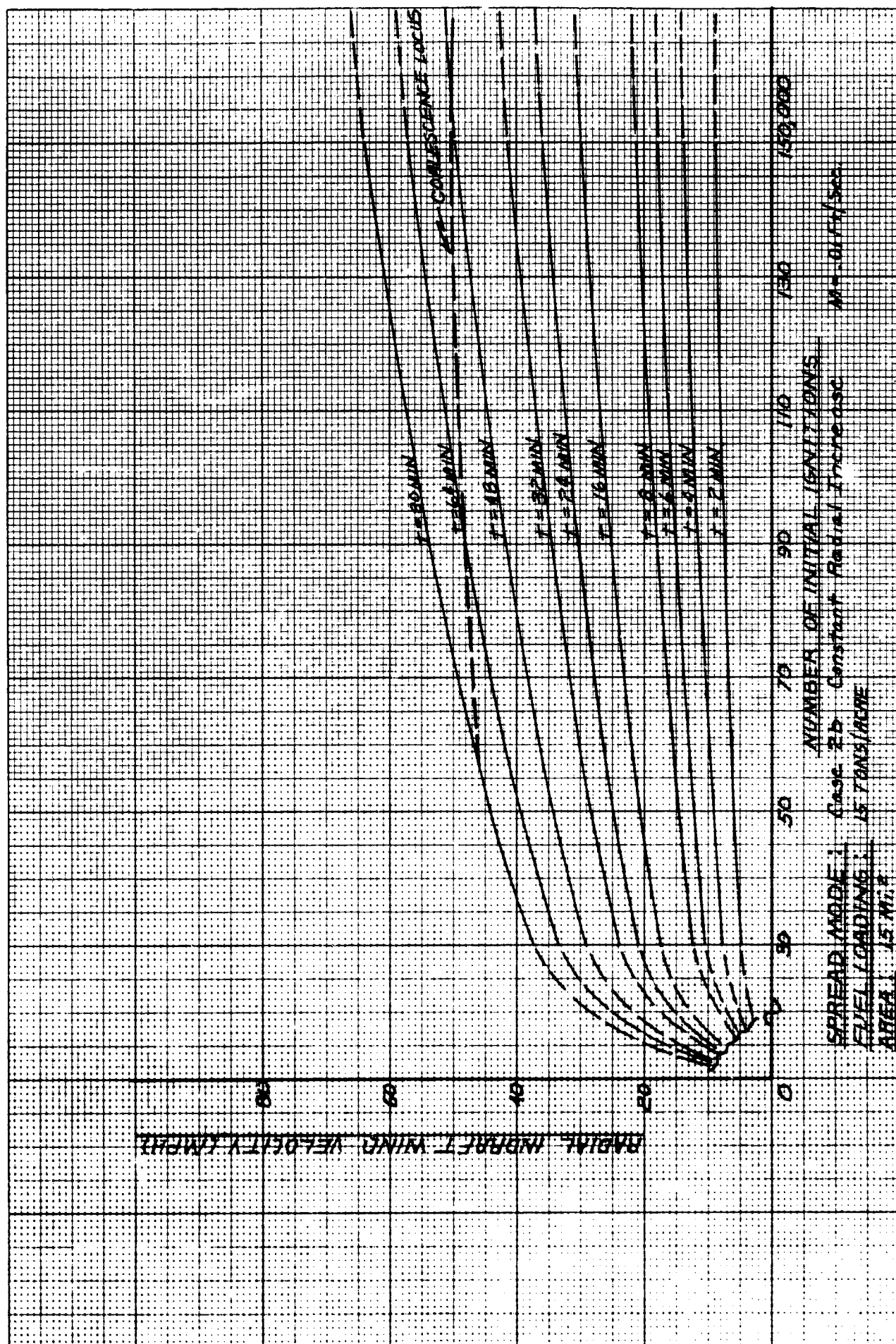


Fig. IV-39



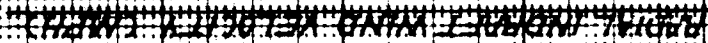


Fig. IV-40

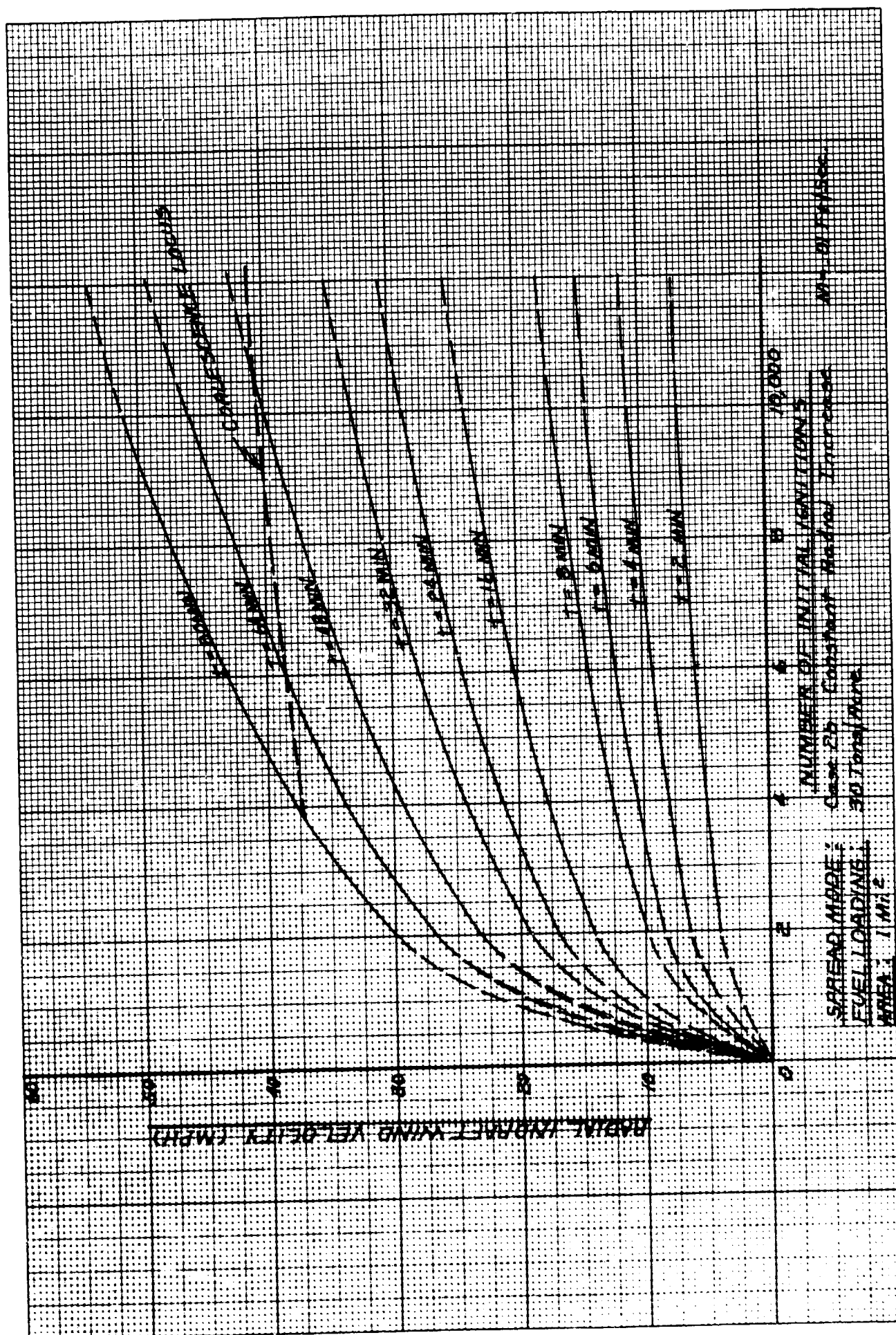


Fig. IV-41

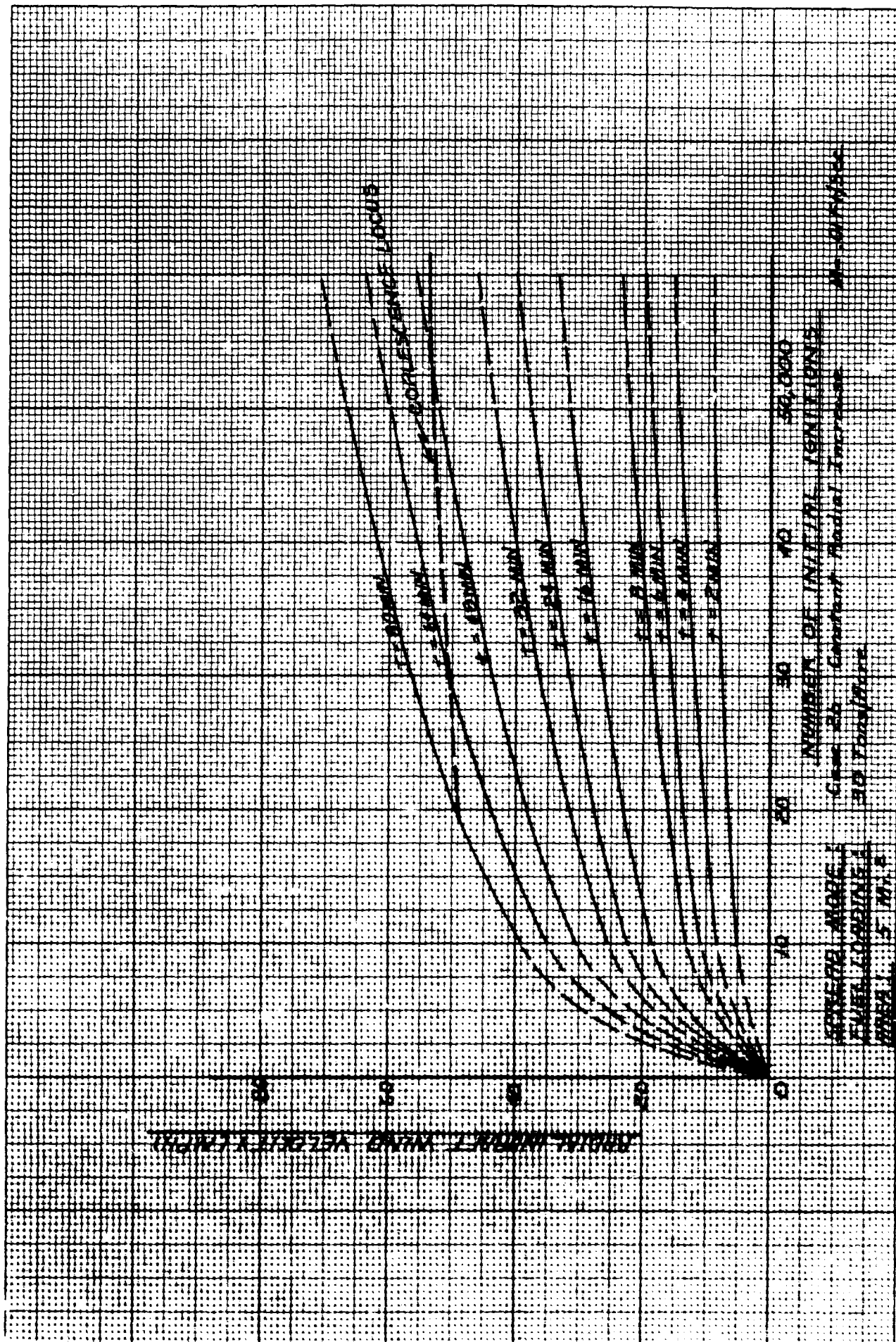


Fig. IV-42

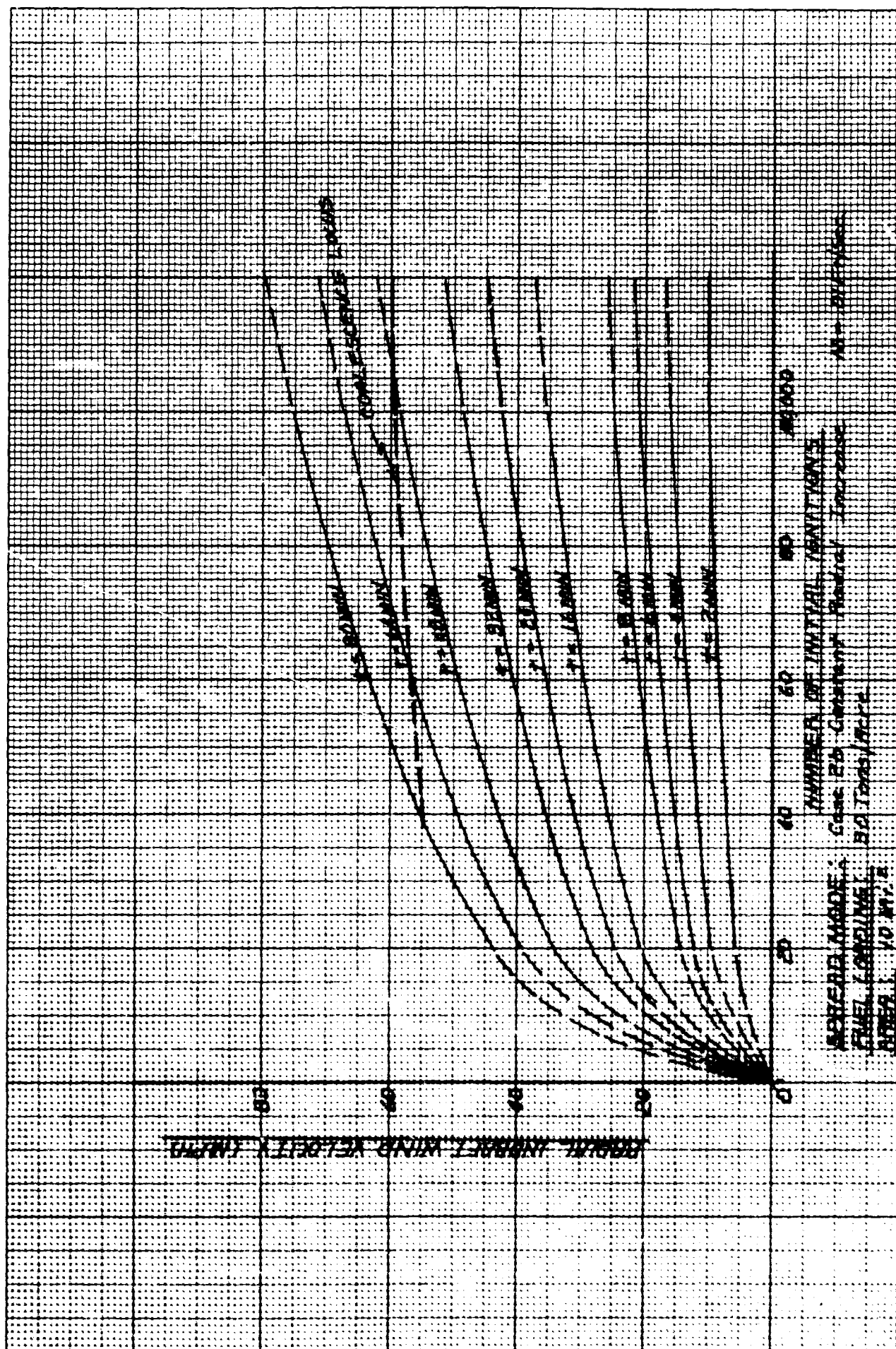


Fig. IV-43



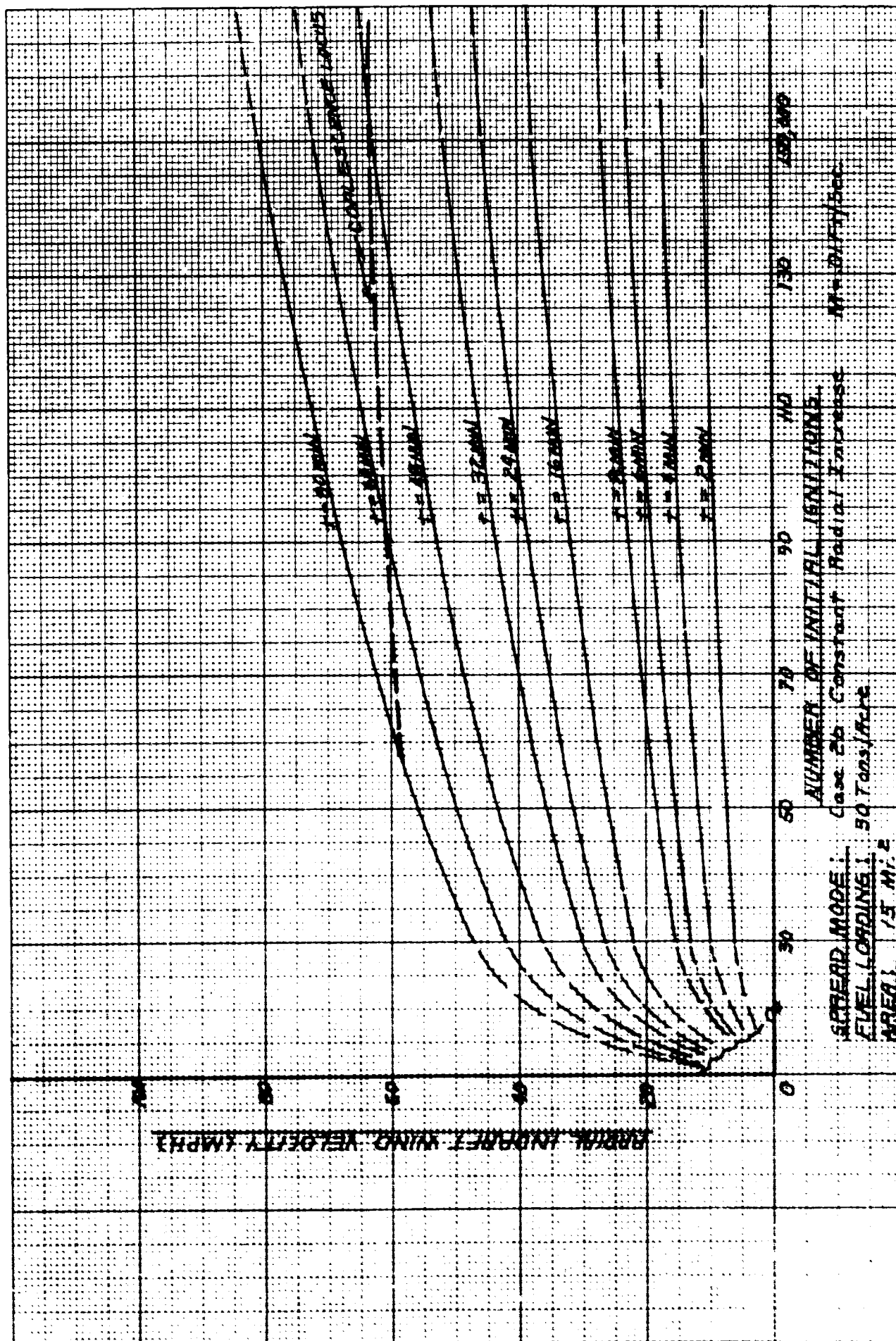


Fig. IV-44

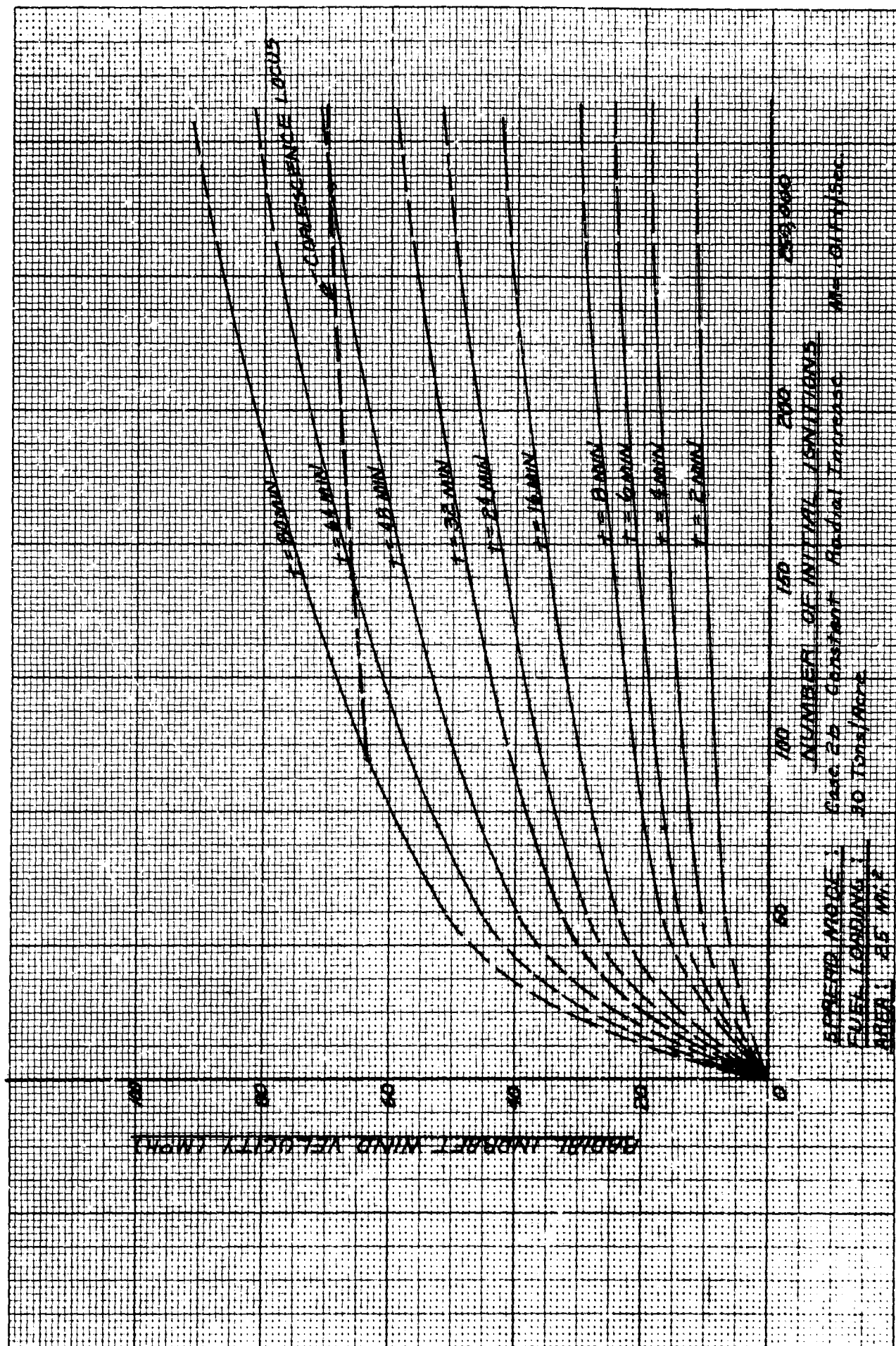


Fig. IV-45

## APPENDIX V

### SENSITIVITY CURVES

The following seven sets of curves are based upon the rationale and parameter values discussed in Appendix II and are drawn from the output of Part II of the computer program listed in Appendix III.

Each family of curves represents  $\frac{\partial v}{\partial \mu_i}$  as a function of  $\mu_i$  for ten different times with the other parameters  $\mu_j$  ( $j \neq i$ ) held at their "representative value" as listed in Table II-I.

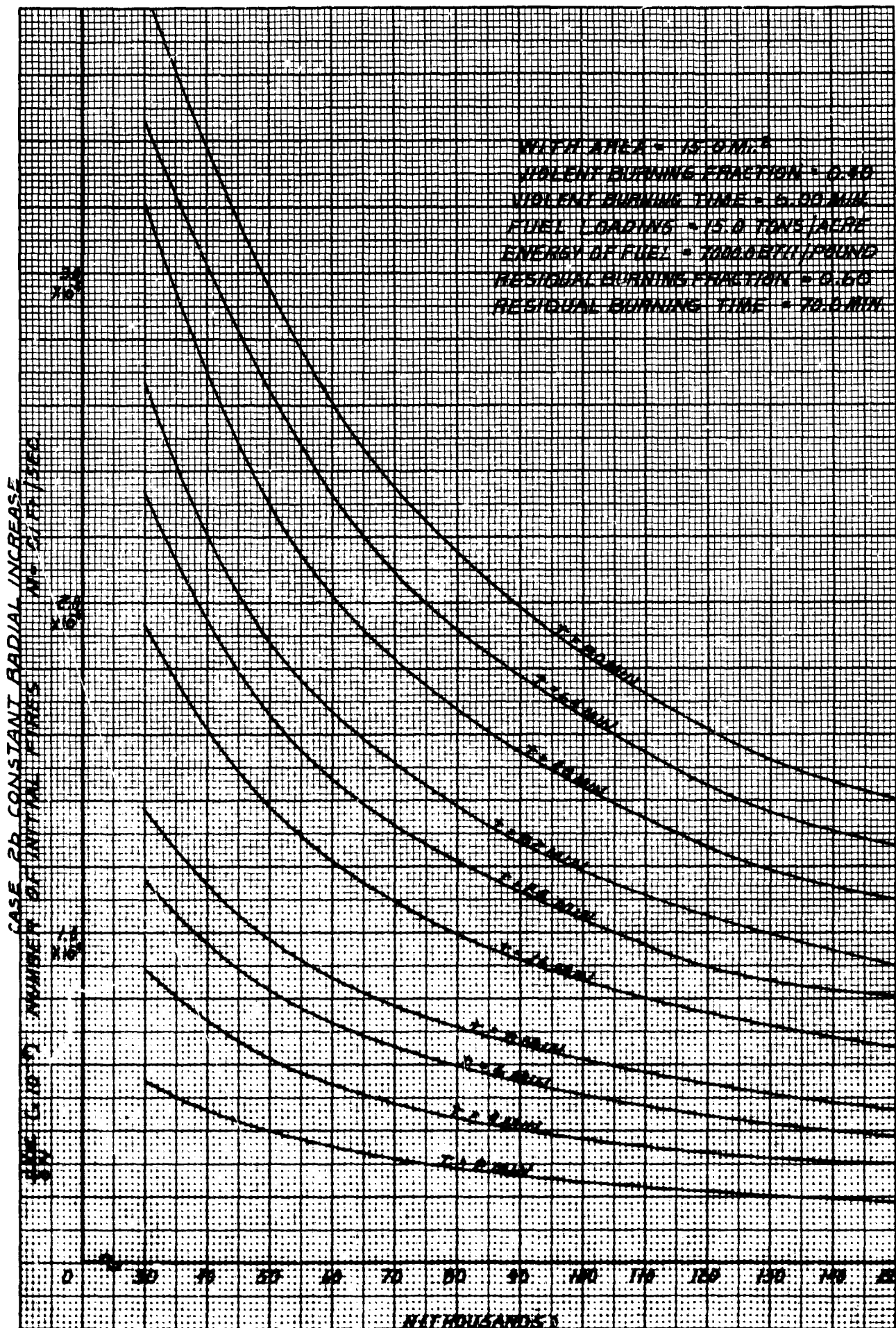


Fig. V-1

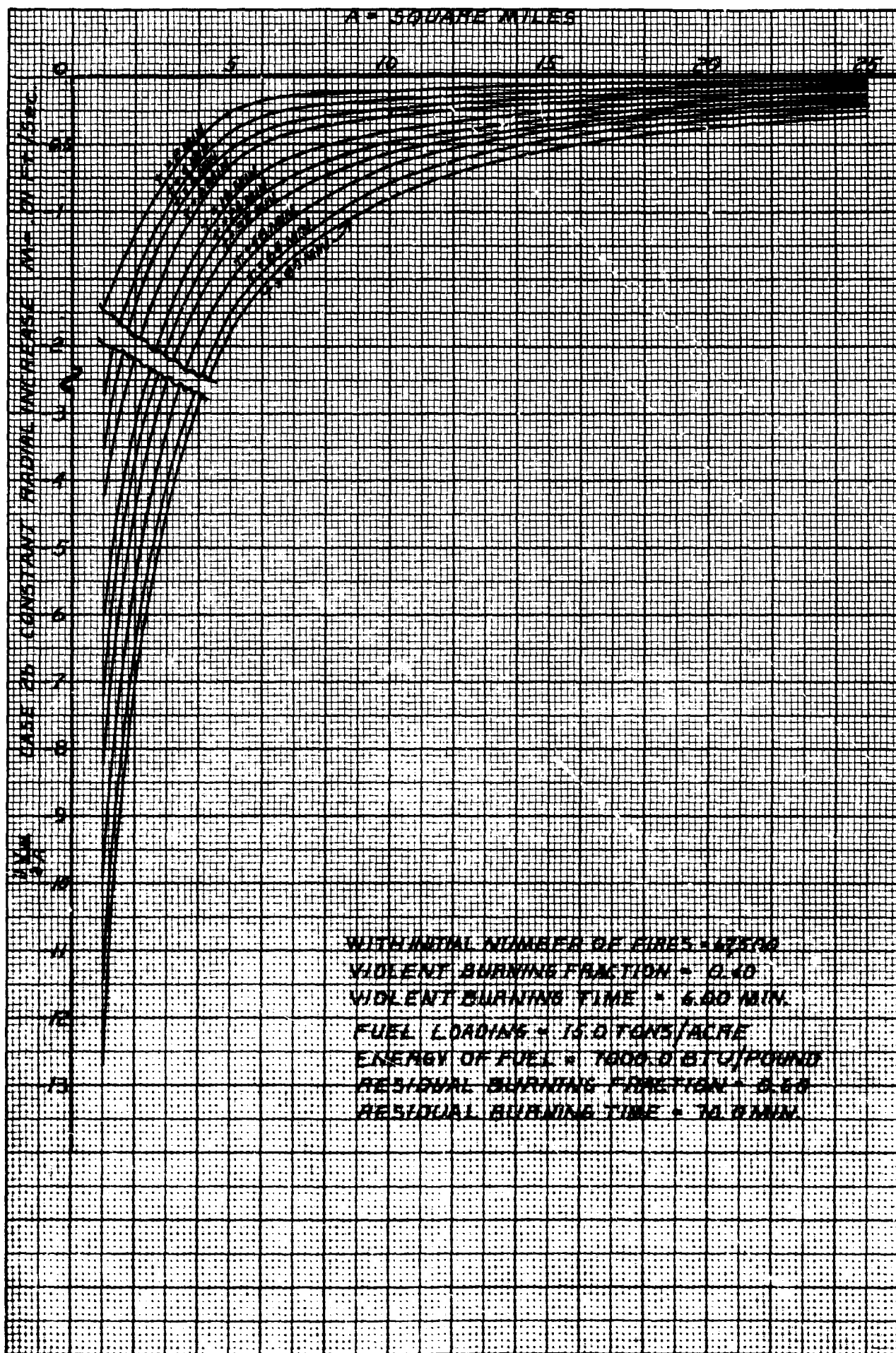


Fig. V-2



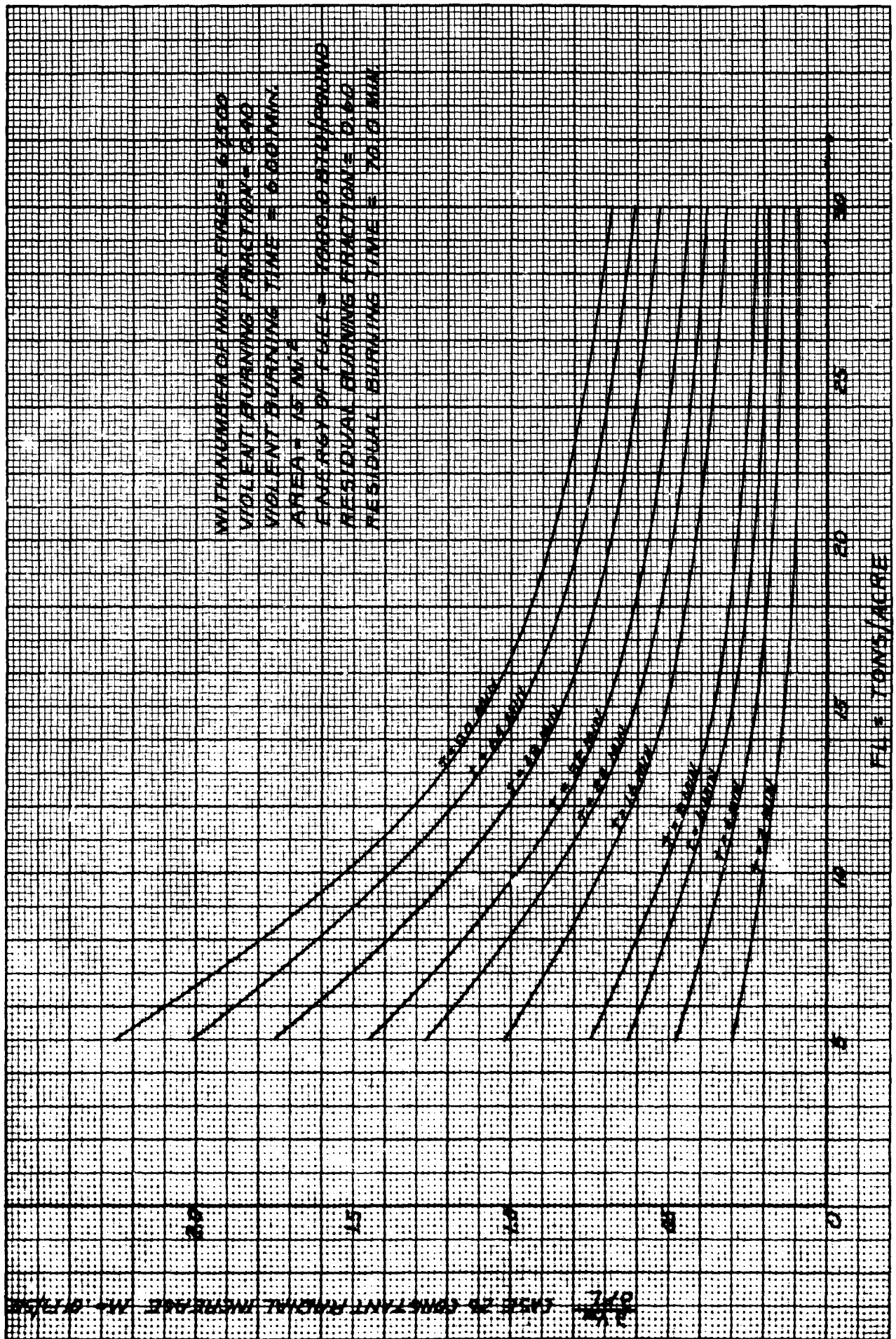


Fig. V-3

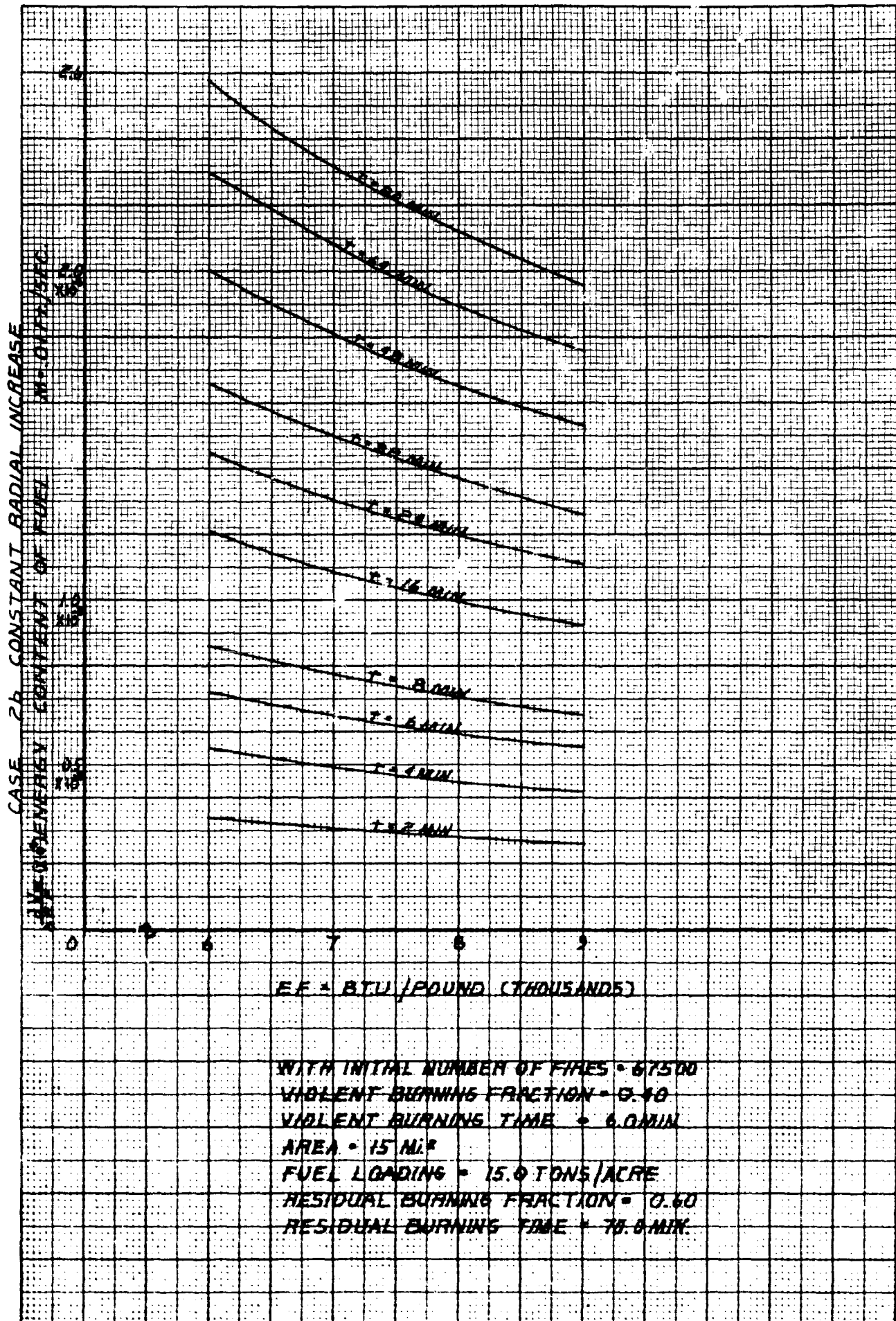


Fig. V-4

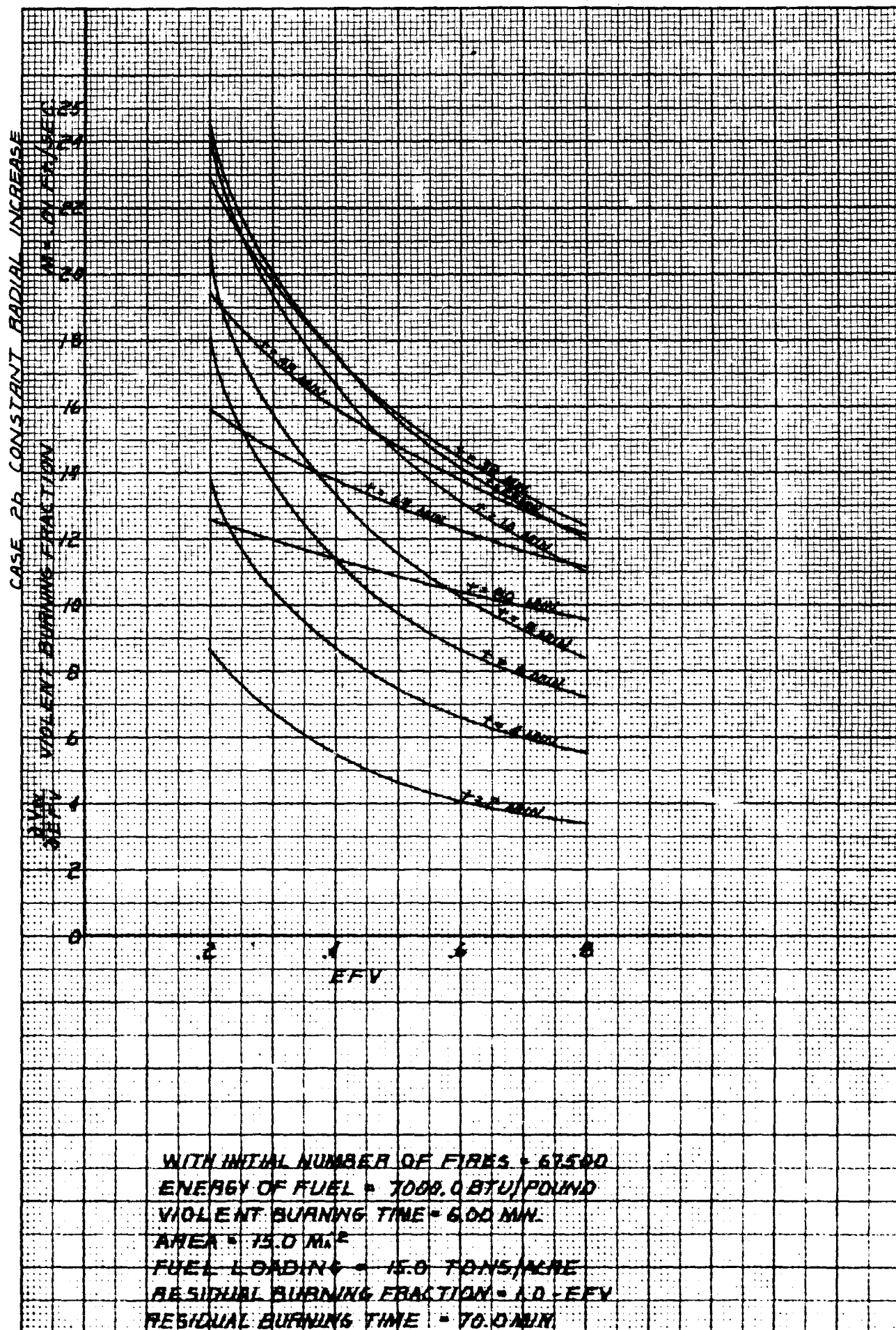


Fig. V-5



K-E 10 X 10 TO 1/2 INCH 40 1323  
 7 1/2 INCHES MADE IN U.S.A.  
 KLUPPEL & ESSER CO.

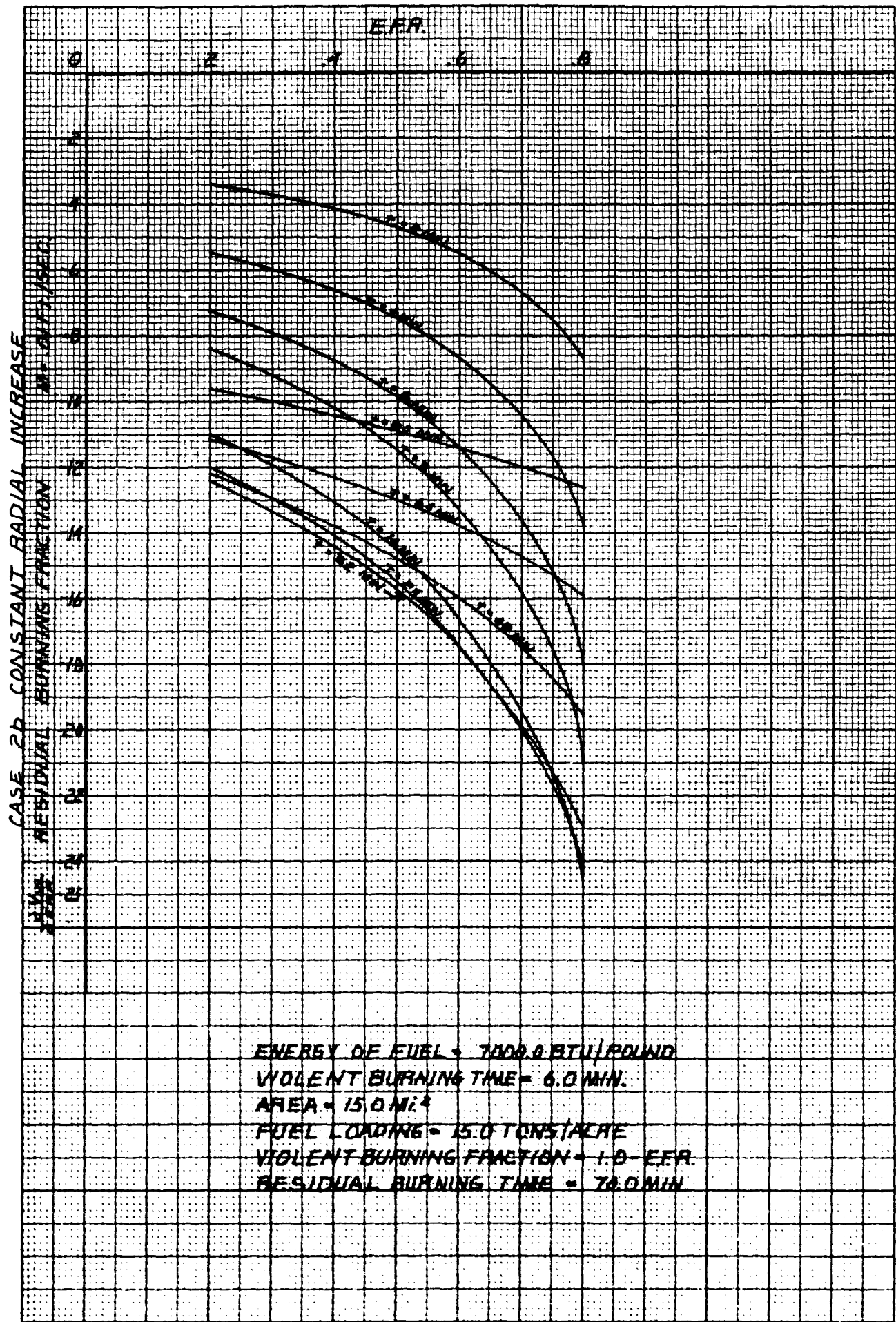


Fig. V-6

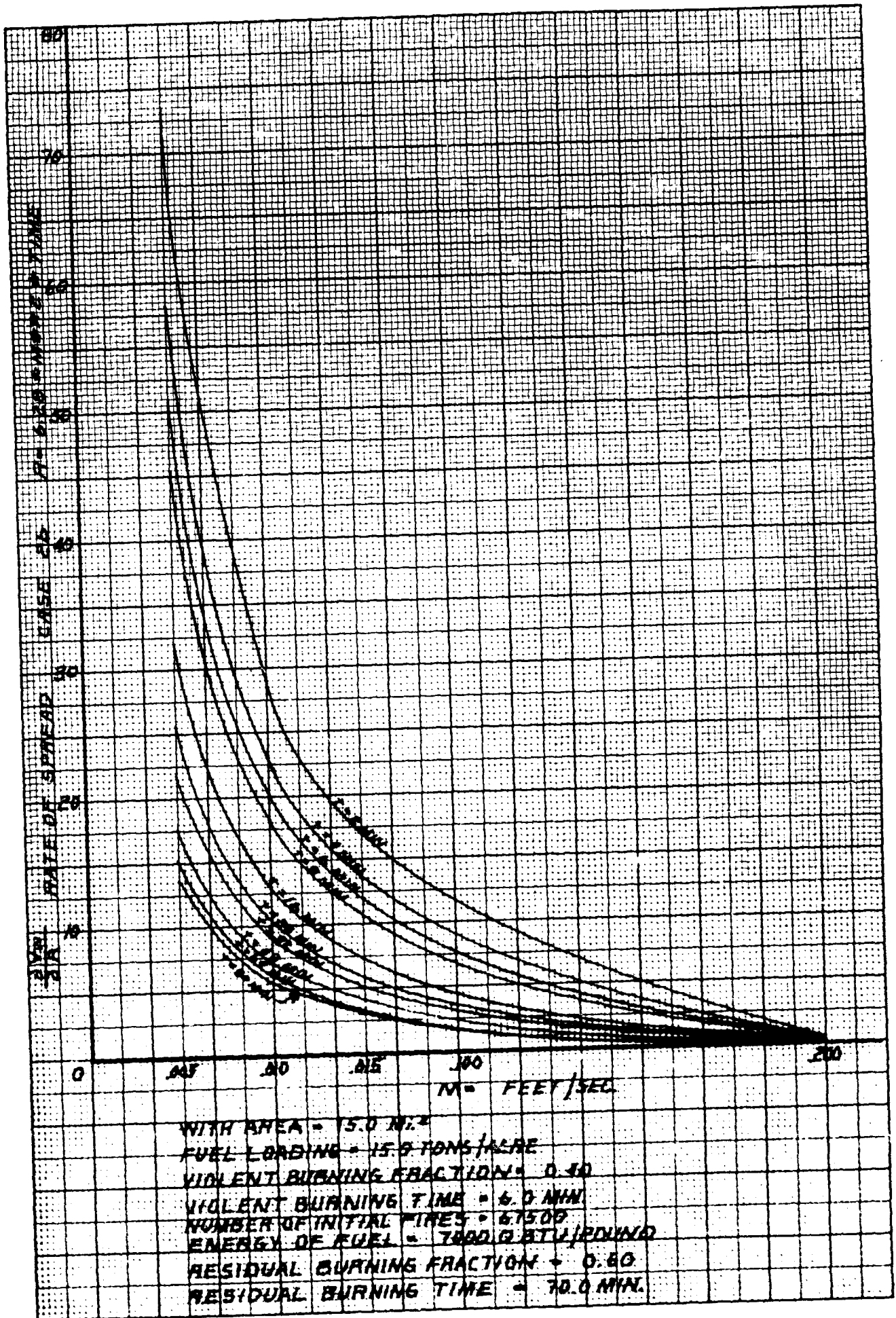


Fig. V-7

## APPENDIX VI

### ACCELERATED SPREAD STUDY

#### VI.1 General

Given  $n$  initial point fires distributed uniformly in an area  $A$  such that the initial separation distances between any fire and its nearest neighbors are equal, then  $D$ ,  $x$ , and  $r_c$  are defined in Fig. VI-1 for any two fires.

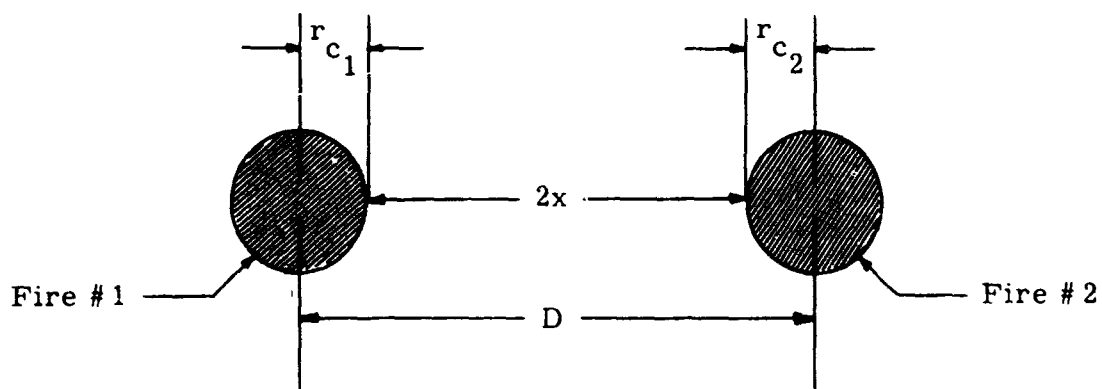


Fig. VI-1

Assume that  $r_{c1} = r_{c2} = \phi(t)$ , that both fires maintain essentially circular fronts as the fires spread, and the radius at any time  $t$  is  $r_c$  for each fire.

Let  $M$  represent the rate of radial spread in ft/min, so that

$$M = \frac{dr_c}{dt} \quad (VI.1)$$

$M$ ,  $x$ , and  $r_c$  are to be determined as functions of time for four initial spread modes, with accelerated spread beginning at some value of  $r_c$ .

## VI.2 Accelerated Spread Relations \*

Assume that for  $r_c \geq [\sqrt{A/4n} - 3F]$ , i. e., when  $t > t_a$ , spread is accelerated according to the hyperbolic relation

$$Mx = 3F \cdot M_a, \quad (VI.2)$$

where

- A is the fire area (sq ft),
- n is the total number of fires in area A,
- F is the flame height (assume  $F = 3$  ft),
- $t_a$  is the time at which accelerated spread begins,
- x is the distance of one fire front from the point of merging,
- 2x is the minimum separation between fires (ft), and
- $M_a$  is the value of M at  $t_a$ , which is the start of the accelerated spread, i. e.,

$$r_c \text{ at } t_a = \sqrt{A/4n} - 3F$$

NOTE:  $D = \sqrt{A/n}$ ; therefore, since  $x = \frac{1}{2} D - r_c$ ,

$$x \text{ at } t_a = 3F = 9 \text{ ft}.$$

## VI.3 Initial Spread Mode One

For initial spread mode one, take, for  $0 \leq r_c \leq [\sqrt{A/4n} - 3F]$ ,

---

\* Provided by Mr. Craig C. Chandler, Division of Fire Research, U. S. Forest Service, Washington, D. C.

$$\left. \begin{aligned} M &= 0 \quad \text{if } t \leq 1/6760 \text{ min} \\ M &= \frac{1.27}{2\pi} \log_{10}(6760 t) \quad \text{for } \frac{1}{6760} < t \leq t_a \end{aligned} \right\} \quad (\text{VI. 3})^*$$

Then, since

$$r_c(t) = \int_0^t M dt = \frac{1.27}{2\pi} \int_{\frac{1}{6760}}^t \log_{10}(6760 t) dt \quad , \quad (\text{VI. 4})$$

$$r_c(t) = \frac{1.27}{2\pi(\ln 10)} \left[ t \{ \ln(6760 t) - 1 \} + \frac{1}{6760} \right] \quad , \quad (\text{VI. 5})$$

and

$$x(t) = \frac{1}{2} D - r_c(t) = \frac{1}{2} \sqrt{A/n} - r_c(t) \quad , \quad (\text{VI. 6})$$

where  $r_c(t)$  is the value of  $r_c$  at time  $t$ .

#### VI. 4 Initial Spread Mode Two

For initial spread mode two, take, for  $0 \leq r_c \leq [\sqrt{A/4n} - 3F]$  ,

$$\left. \begin{aligned} M &= 0 \quad \text{if } t \leq 1/0.91 \text{ min} \\ M &= \frac{6.67}{2\pi} \log_{10}(0.91 t) \quad \text{for } \frac{1}{0.91} < t \leq t_a \end{aligned} \right\} \quad (\text{VI. 7})^*$$

As before, integration of Eq. (VI. 7) yields

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\* Provided by Mr. Craig C. Chandler, Division of Fire Research, U. S. Forest Service, Washington, D. C.

$$r_c(t) = \frac{6.67}{2\pi(\ln 10)} \left[ t[\ln(0.91 t) - 1] + \frac{1}{0.91} \right] ; \quad (\text{VI. 8})$$

and, also

$$x(t) = \frac{1}{2} D - r_c(t) = \frac{1}{2} \sqrt{A/n} - r_c(t) . \quad (\text{VI. 9})$$

#### VI. 5 Initial Spread Mode Three

Consider now the case of constant rate of radial increase for  $t \leq t_a$ , with

$$M = 0.01 \text{ ft/sec} = 0.6 \text{ ft/min} . \quad (\text{VI. 10})$$

In this case,

$$r_c(t) = 0.6 t , \quad (\text{VI. 11})$$

and, as before

$$x(t) = \frac{1}{2} D - r_c(t) . \quad (\text{VI. 12})$$

#### VI. 6 Initial Spread Mode Four

Also, consider the case of constant rate of area increase up to  $t = t_a$ , i. e.,

$$\frac{dA}{dt} = K_1 = 5 \text{ ft}^2/\text{sec} = 300 \text{ ft}^2/\text{min} . \quad (\text{VI. 13})$$

Now

$$\frac{dA}{dt} = \frac{d(\pi r_c^2)}{dt} = 2\pi r_c \frac{dr_c}{dt} = 2\pi r_c M , \quad (\text{VI. 14})$$

and equating (VI. 13) with (VI. 14) yields

$$2\pi r_c M = 300 \text{ ft}^2/\text{min} . \quad (\text{VI. 15})$$

Taking Eq. (VI. 15) and remembering that

$$M = \frac{dr_c}{dt} = r'_c ,$$

we have that

$$r_c r'_c = \frac{300}{2\pi} = C \quad (VI. 16)$$

with the initial condition that  $r_c(0) = 0$ .

Hence,

$$r_c(t) = \sqrt{2Ct} = \sqrt{\frac{300t}{\pi}} , \quad (VI. 17)$$

and, as before

$$x(t) = \frac{1}{2}D - r_c(t) . \quad (VI. 18)$$

Also, differentiation of Eq. (VI. 17) yields

$$M = \sqrt{\frac{75}{\pi t}} . \quad (VI. 19)$$

#### VI. 7 Method of Calculation

A computer program has been written based upon the foregoing which calculates  $M$ ,  $r_c$ , and  $x$  as functions of time for  $0 \leq r_c < \frac{1}{2}D$ . A listing of this program and its input requirements is included in Appendix VII.

#### VI. 8 Results

The results of calculations with the above program are presented graphically in Appendix VIII.

## APPENDIX VII

### ACCELERATED SPREAD PROGRAM

#### VII. 1 General

The following program is based upon the accelerated spread rationale explained in Appendix VI, and calculates spread rate ( $M$ ), fire radius ( $r_c$ ), and distance to merging ( $x$ ) for each of the four initial spread modes discussed in Appendix VI, with acceleration for each mode beginning when  $x \leq 3F$ , where  $F$  represents the flame height. The program is written in FORTRAN IV for an IBM System/360 Model 40G digital computer. The program is in three parts. The first part performs the calculations for each initial spread mode. SUBROUTINE PRINT prints the results of these calculations up to the point of acceleration, and SUBROUTINE ACC performs the calculations and prints the results for each initial mode after acceleration begins.

#### VII. 2 Data Cards

The first card has format I12 and contains NSETS, the number of data sets to be used in the run.

Each data set consists of a single card with format 5E12. 4 containing the following inputs:



<u>Column</u>	<u>Program Symbol</u>	<u>Units</u>	<u>Variable</u>
1-12	D	feet	Initial separation between fires
13-24	F	feet	Flame height
25-36	TINC	minutes	Time increment of calculation for initial spread
37-48	TM1	minutes	Spread start time for Mode 1
49-60	TM2	minutes	Spread start time for Mode 2

NOTE: Due to the form of the equations for initial spread modes one and two, TM1 must be greater than 1/6760 minutes and TM2 must be greater than 1/0.91 minutes.

### VII. 3 Program Listing

(See following pages.)

C	PROGRAM SPREAD	1
	DIMENSION T(1500),M(1500),RC(1500),X(1500)	2
	REAL M,MA	3
	PI=3.14159	4
	READ (1,1) NSETS	5
1	FORMAT (I12)	6
C	NSETS IS THE NUMBER OF DATA SETS	7
	DO 21 K=1,NSETS	8
	READ (1,2) D,F,TINC,TM1,TM2	9
C	D IS THE INITIAL SEPARATION BETWEEN FIRES IN FEET	10
C	F IS THE FLAME HEIGHT IN FEET	11
C	TINC IS THE TIME INCREMENT IN MINUTES FOR INITIAL SPREAD	12
C	TM1 IS THE SPREAD START TIME FOR MODE ONE	13
C	TM2 IS THE SPREAD START TIME FOR MODE TWO	14
C	RC IS THE FIRE RADIUS IN FEET	15
C	X IS THE DISTANCE TO MERGING IN FEET	16
C	M IS THE RATE OF RADIAL SPREAD IN FEET PER MINUTE	17
C	T IS TIME IN MINUTES	18
2	FORMAT (5E12.4)	19
	MODE=0	20
	T(1)=TINC	21
C	THIS LOOP CALCULATES SPREAD FOR MODE ONE	22
	TEST=3.0*F	23
	DO 7 I=1,1000	24
	IF (T(I)-TM1) 3,3,4	25
3	M(I)=0	26
	RC(I)=0	27
	GO TO 5	28
4	M(I)=1.27/(2.0*PI)*ALOG10(6760.0*T(I))	29
	RC(I)=1.27/(2.0*PI*ALOG(10.0))*(T(I)*(ALOG(6760.0*T(I))-1.0)	30
	+1.0/6760.0)	31
5	X(I)=0.5*D-RC(I)	32
	II=I	33
	IF (X(I)-TEST) 8,8,6	34
6	T(I+1)=(I+1)*TINC	35
7	CONTINUE	36
8	MA=M(II)	37
	TA=T(II)	38
	XA=X(II)	39
	RA=RC(II)	40
	MODE=MODE+1	41
	CALL PRINT (X,M,T,RC,II,MODE,D,F)	42
	CALL ACC (XA,MA,TA,RA,X,M,T,RC,MODE,F)	43
	GO TO (9,15,18,21),MODE	44
9	T(1)=TINC	45
C	THIS LOOP CALCULATES SPREAD FOR MODE TWO	46
	DO 14 I=1,1000	47
	IF (T(I)-TM2) 10,10,11	48
10	M(I)=0.0	49
	RC(I)=0.0	50
	GO TO 12	51
11	M(I)=6.67/(2.0*PI)*ALOG10(0.91*T(I))	52

	RC(I)=6.67/(ALOG(10.0)*2.0*PI)*(T(I)*(ALOG(0.91*T(I))-1.0)	53
	\$+1.0/0.91)	54
12	X(I)=0.5*D-RC(I)	55
	II=I	56
	IF (X(I)-TEST) 8,8,13	57
13	T(I+1)=(I+1)*TINC	58
14	CONTINUE	59
15	T(I)=TINC	60
C	THIS LOOP IS FOR SPREAD MODE THREE, CONSTANT RADIAL INCREASE	61
	DO 17 I=1,1000	62
	M(I)=0.6	63
	RC(I)=0.6*T(I)	64
	X(I)=0.5*D-RC(I)	65
	II=I	66
	IF (X(I)-TEST) 8,8,16	67
16	T(I+1)=(I+1)*TINC	68
17	CONTINUE	69
18	T(I)=TINC	70
C	THIS LOOP CALCULATES SPREAD FOR MODE FOUR	71
	DO 20 I=1,1000	72
	M(I)=SQRT(75.0/(PI*T(I)))	73
	RC(I)=SQRT((300.0*T(I))/PI)	74
	X(I)=0.5*D-RC(I)	75
	II=I	76
	IF (X(I)-TEST) 8,8,19	77
19	T(I+1)=(I+1)*TINC	78
20	CONTINUE	79
21	CONTINUE	80
	RETURN	81
	END	82
	SUBROUTINE PRINT (X,M,T,RC,II,MODE,D,F)	83
	DIMENSION X(1),M(1),T(1),RC(1)	84
1	FORMAT (1H1,10X,19HINITIAL SEPARATION=,F12.4,10X,13HFLAME HEIGHT=	85
	\$,F12.4,10X,21HSPREAD MODE IS NUMBER,15)	86
	NPG=II/96	87
	L=II-NPG*96	88
	M1=1	89
	M2=96	90
	DO 4 K=1,NPG	91
	WRITE (3,1) D,F,MODE	92
	WRITE (3,2)	93
2	FORMAT (1H0,1X,2(12X,4HTIME,5X,11HSPREAD RATE,5X,11HFIRE RADIUS	94
	\$,3X,14HMEPGE DISTANCE))	95
	WRITE (3,3) (T(J),M(J),RC(J),X(J),J=M1,M2)	96
3	FORMAT (2X,8F16.4)	97
	M1=M1+56	98
	M2=M2+96	99
4	CONTINUE	100
	IF (L) 9,0,5	101
5	IF (NPG) 6,6,7	102
	M1=1	103
	M2=L	104

	GO TO 8	105
7	M2=M1+L-1	106
8	WRITE (3,1) D,F,MODE	107
	WRITE (3,2)	108
	WRITE (3,3) (T(J),M(J),RC(J),X(J),J=M1,M2)	109
9	RETURN	110
	END	111
	SUBROUTINE ACC (XA,MA,TA,RA,X,M,T,RC,MODE,F)	112
C	THIS SUBROUTINE CALCULATES SPREAD RATE, RADIUS, AND	113
C	SEPARATION DISTANCE AFTER ACCELERATION BEGINS	114
	DIMENSION X(1),T(1),M(1),RC(1)	115
	REAL M,MA	116
	DT=.005	117
	X(1)=XA	118
	M(1)=MA	119
	T(1)=TA	120
	RC(1)=RA	121
	DO 1 J=2,1500	122
	X(J)=X(J-1)-M(J-1)*DT	123
	M(J)=3.0*F*MA/X(J)	124
	RC(J)=RA+XA-X(J)	125
	T(J)=TA+DT*(J-1)	126
	IF (X(J)-.05) 2,2,1	127
1	CONTINUE	128
2	LPINC=4	129
	N=J-LPINC+1	130
	LPPG=96*LPINC	131
	NPG=N/LPPG	132
	L=N-NPG*LPPG	133
	M1=1	134
	M2=LPPG	135
	DO 3 KK=1,NPG	136
	WRITE (3,8) MODE	137
	WRITE (3,9)	138
	WRITE (3,10) (T(K),M(K),RC(K),X(K),K=M1,M2,LPINC)	139
	M1=M1+LPPG	140
	M2=M2+LPPG	141
3	CONTINUE	142
	IF (L) 11,11,4	143
4	IF (NPG) 5,5,6	144
5	M1=1	145
	M2=L	146
	GO TO 7	147
6	M2=M1+L-1	148
7	WRITE (3,8) MODE	149
	WRITE (3,9)	150
	WRITE (3,10) (T(K),M(K),RC(K),X(K),K=M1,M2,LPINC)	151
8	FORMAT (1H1,40X,'ACCELERATION PHASE FOR INITIAL SPREAD MODE',15)	152
9	FORMAT (1H0,1X,2(12X,4HTIME,5X,11HSPREAD RATE,5X,11HFIRE RADIUS	153
	5,3X,14HFFGE DISTANCE))	154
10	FORMAT (2X,5F16.4)	155
11	RETURN	156

## APPENDIX VIII

### ACCELERATED SPREAD CURVES

The following eight curves show spread rate (M) as a function of time (t) and fire radius ( $r_c$ ) for each of the four initial spread modes discussed in Appendix VI, with the point at which accelerated spread begins indicated by the symbol ▲ beside each curve.

These curves are drawn from the output of the computer program described in Appendix VII, with an initial separation between fires (D) of 78.8 feet, a flame height (F) of 3.0 feet, TINC = 0.1 minutes, TM1 = .000148 minutes, and TM2 = 1.1 minutes.

The value of D was taken from the formula  $D = \sqrt{A/n}$ , with  $n = A \cdot n_d$ . Using the representative values of A and  $n_d$  as discussed in Appendix II,

$$D = \sqrt{\frac{15.0 (5280)^2}{15.0 \cdot 4500}} = \frac{528}{3} \sqrt{1/5} = 78.8 \text{ ft}.$$

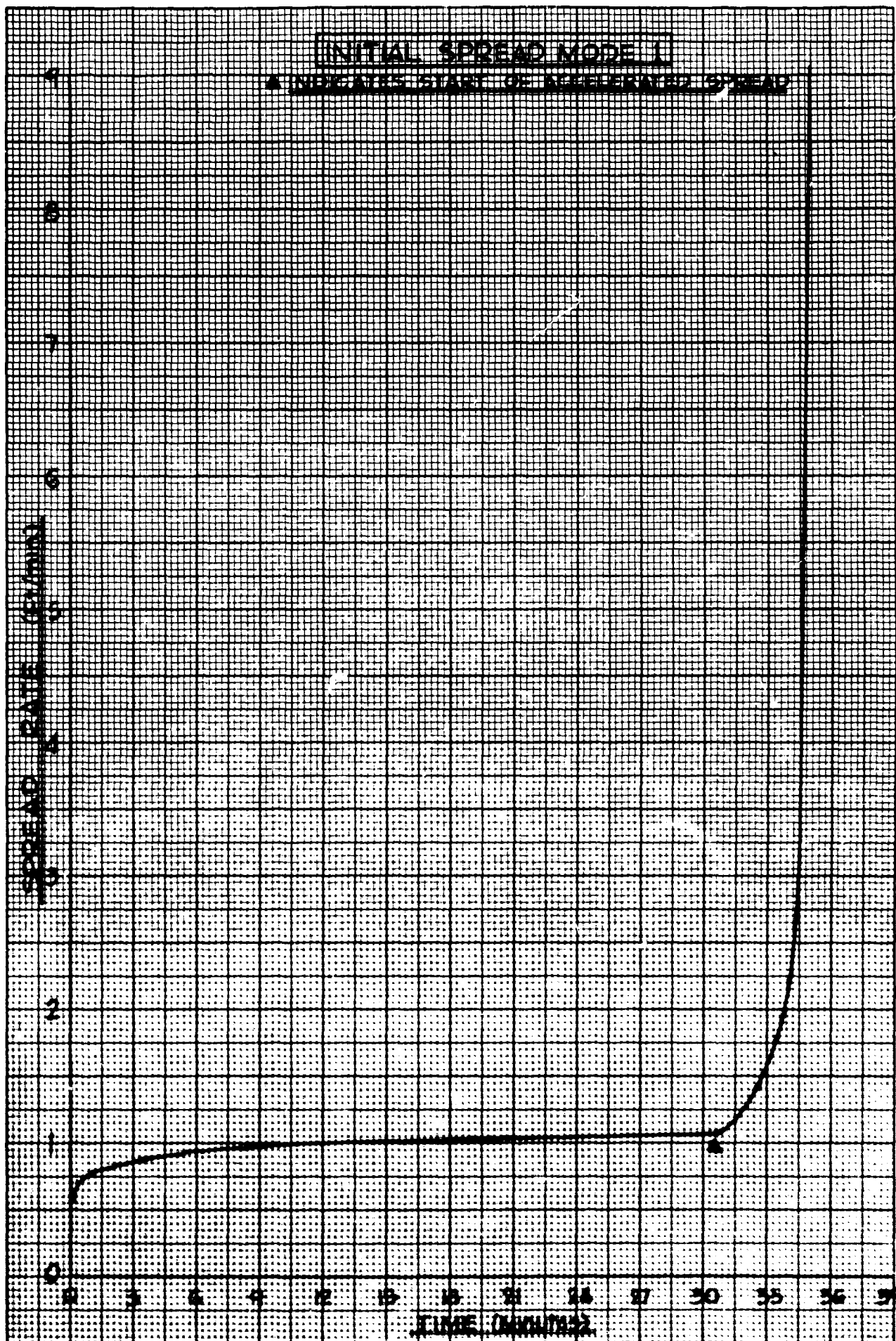


Fig. VIII-1

K-E 10 X 10 TO 15 INCH 48 1323  
7 1/2 INCHES  
KEUFFEL & ESSER CO.

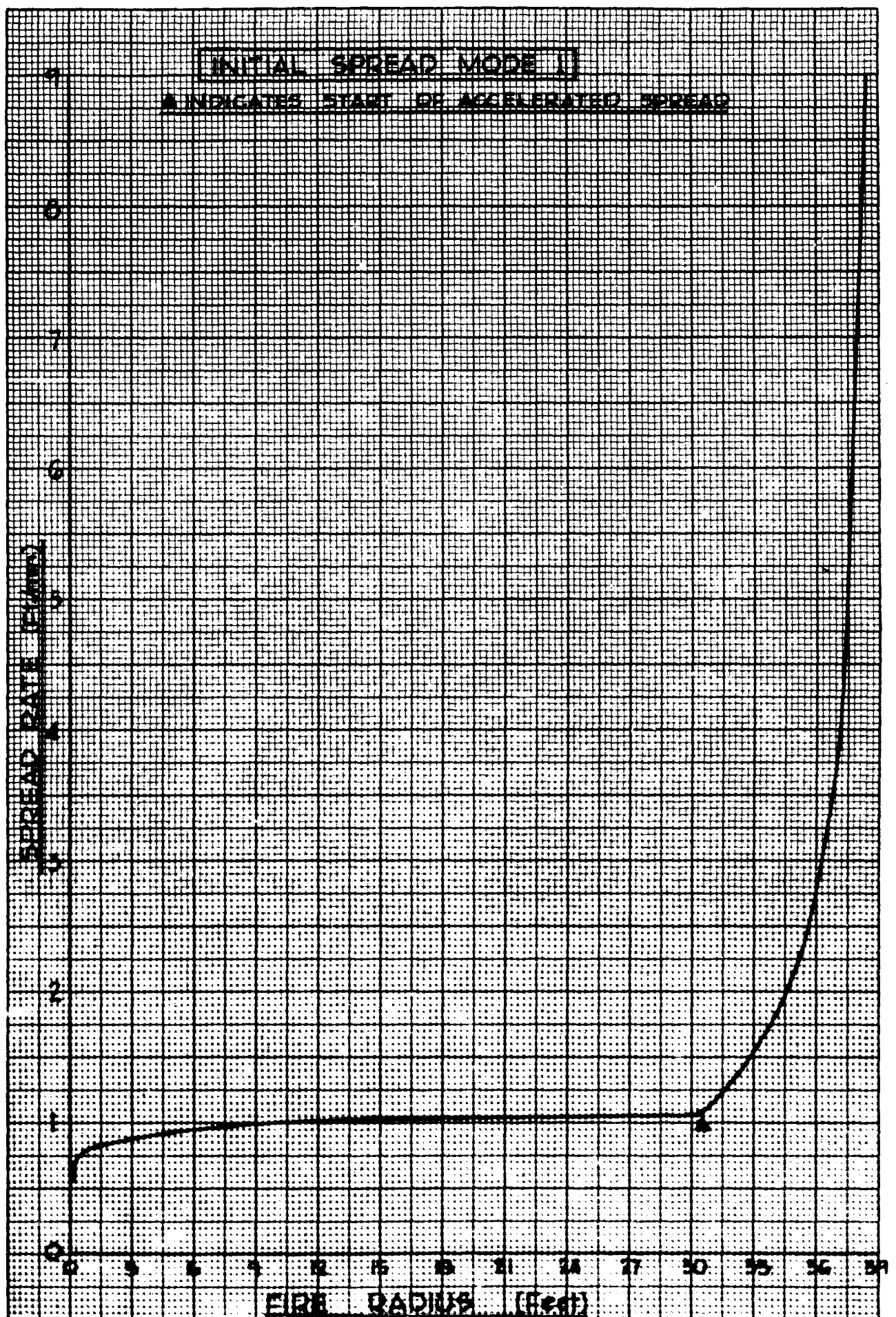


Fig. VIII-2

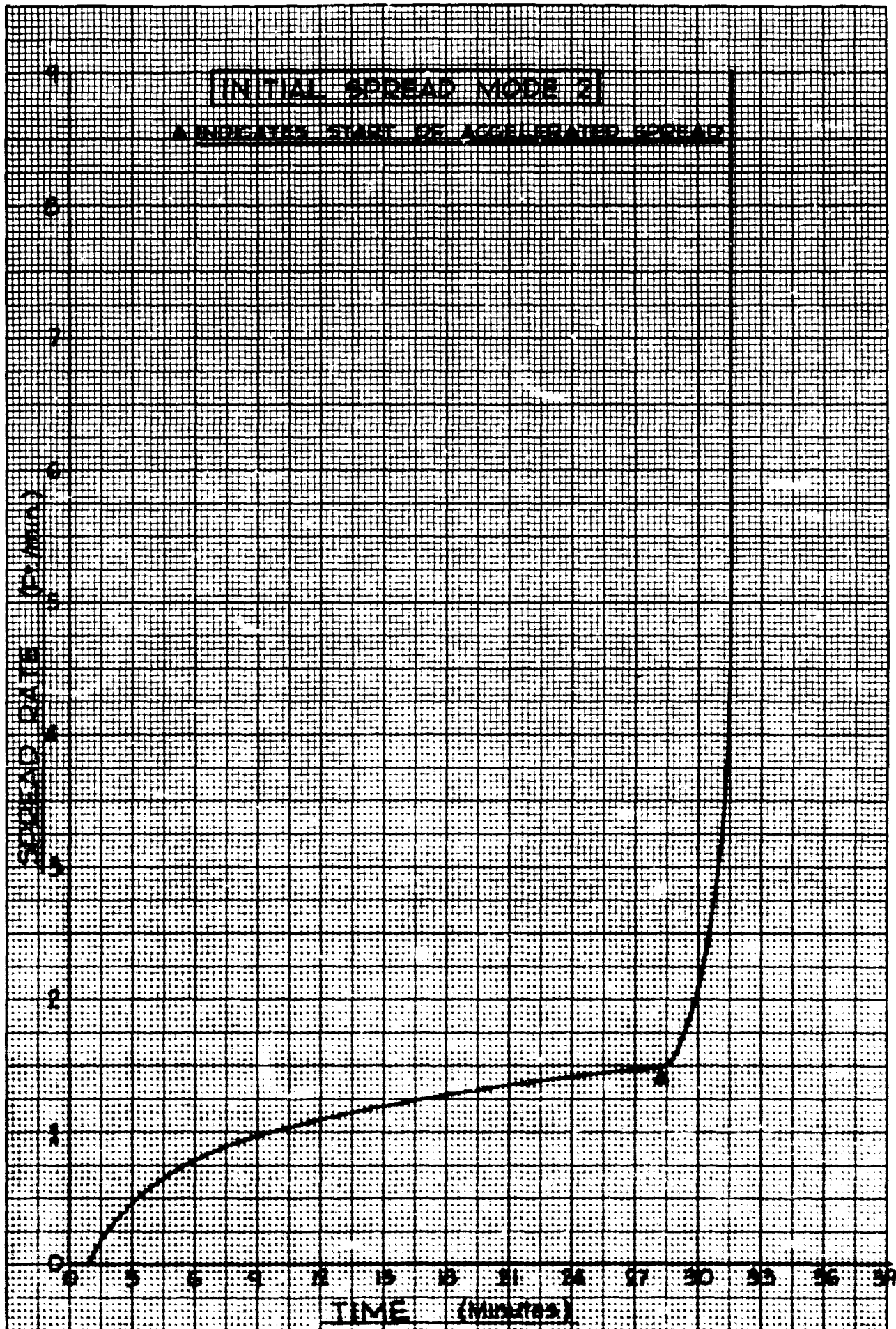


Fig. VIII-3



K-E 10 X 10 TO 1/2 INCM 46 1323  
 7 X 10 INCM 5  
 8 IN. IN U.S.A.  
 BEUPPEL & ESSER CO.

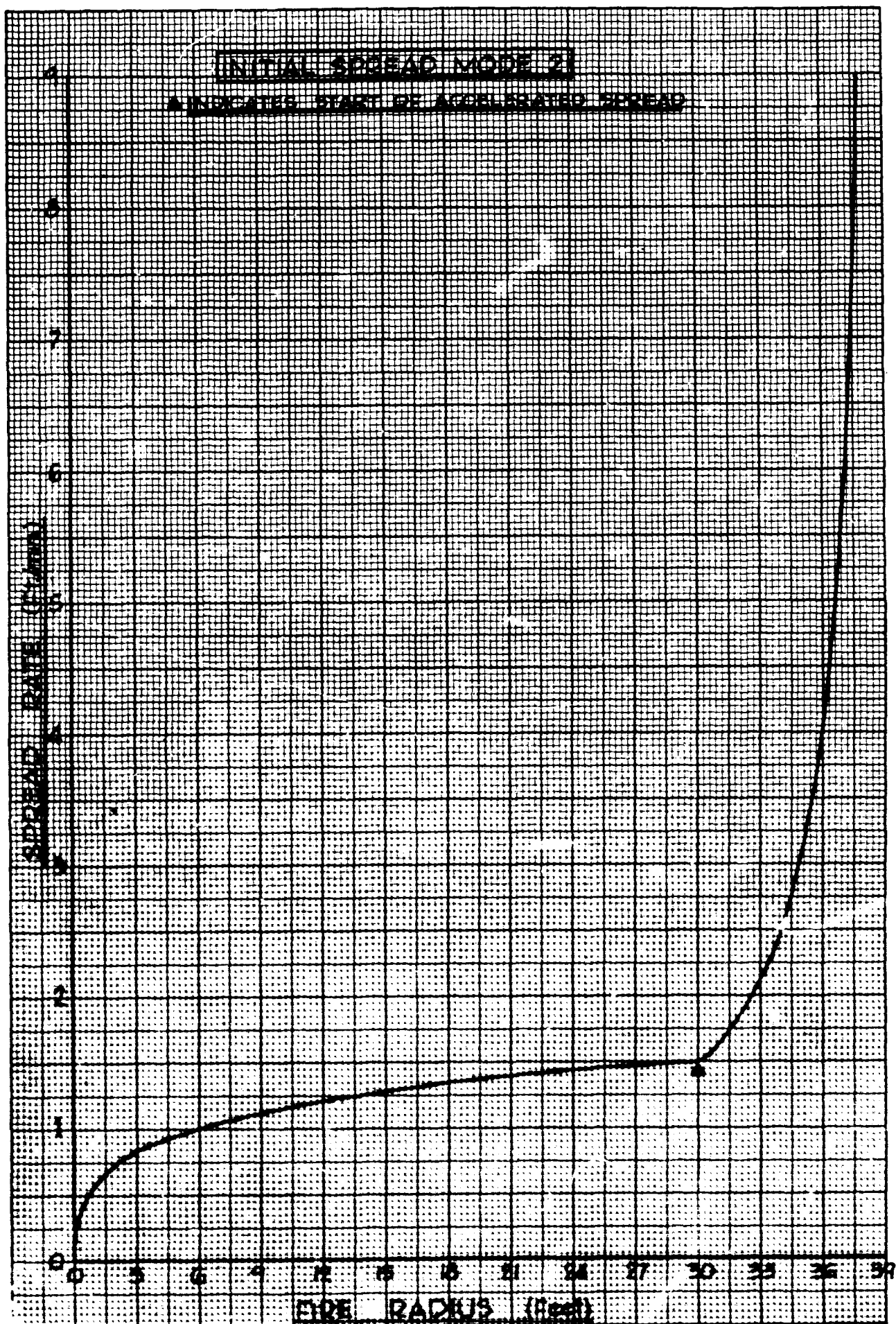


Fig. VIII-4

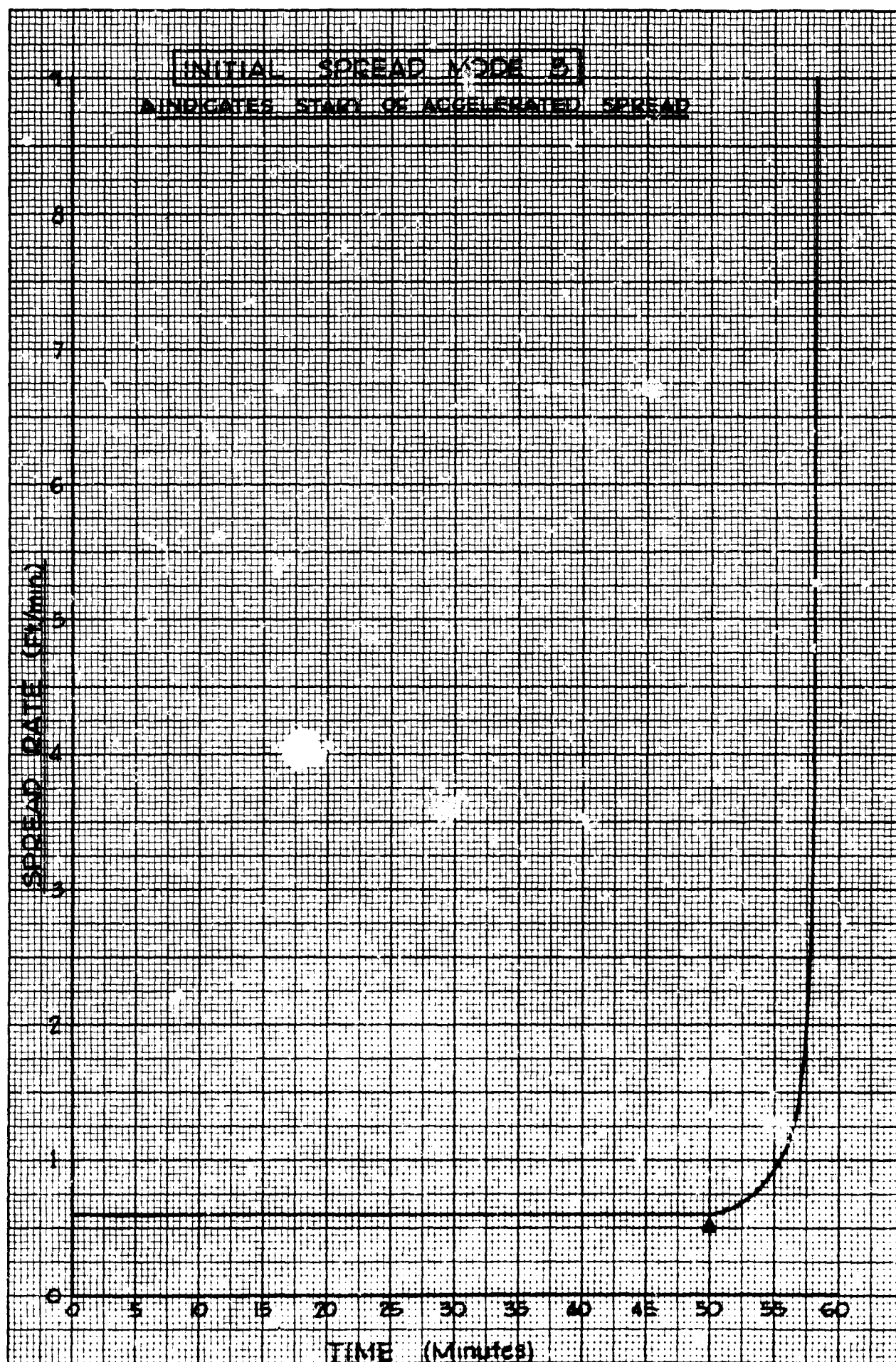


Fig. VIII-5

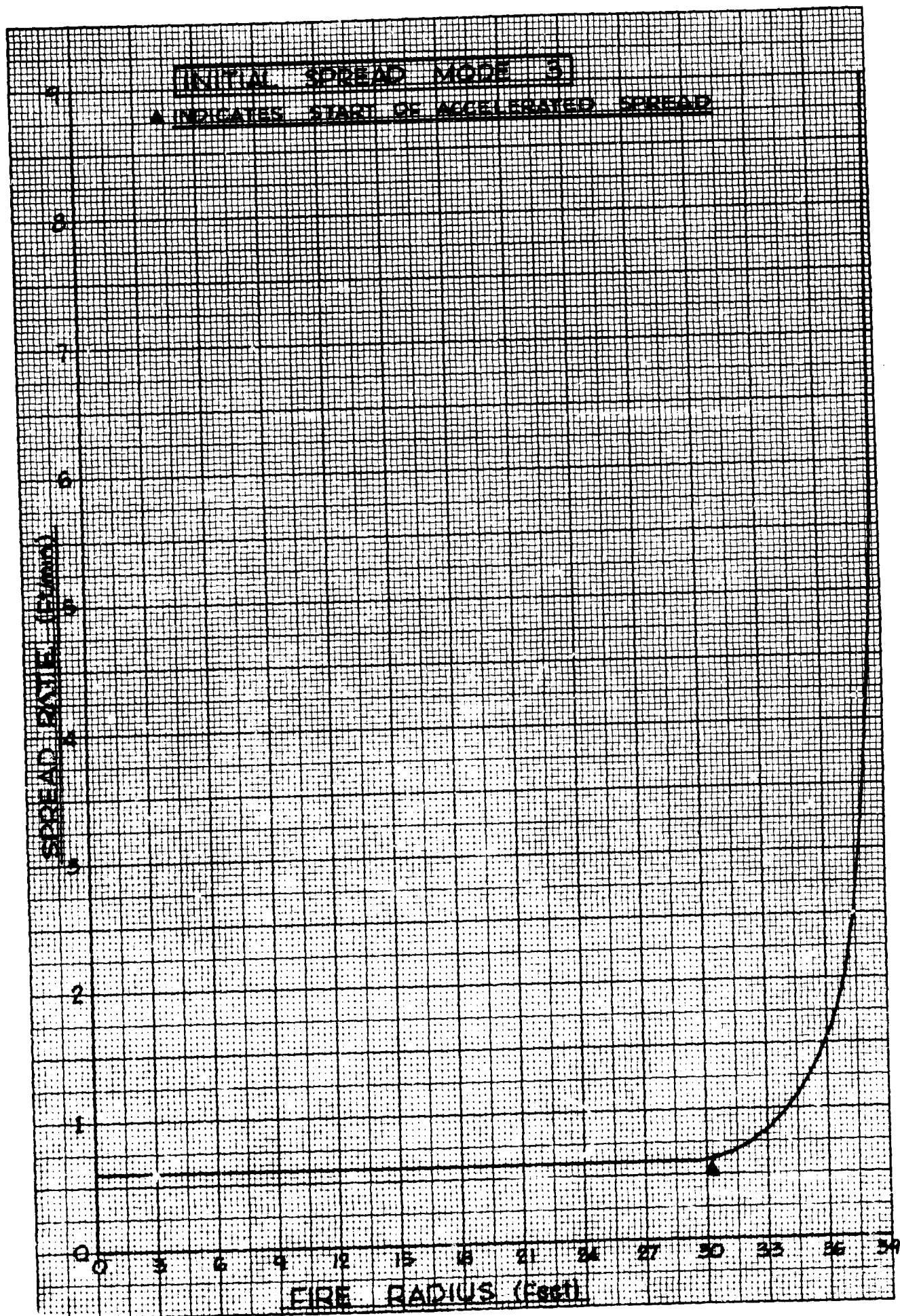


Fig. VIII-6



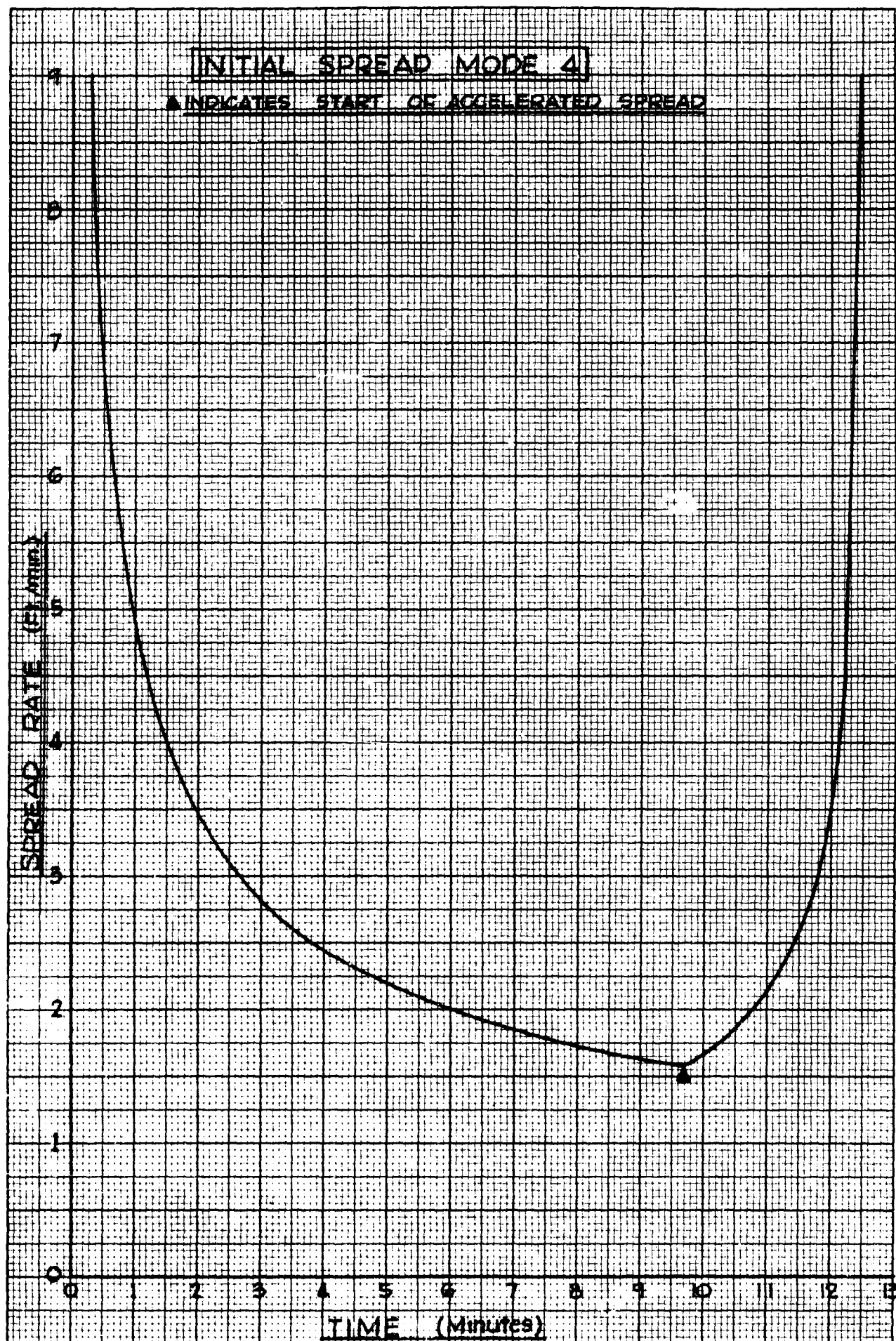


Fig. VII-7

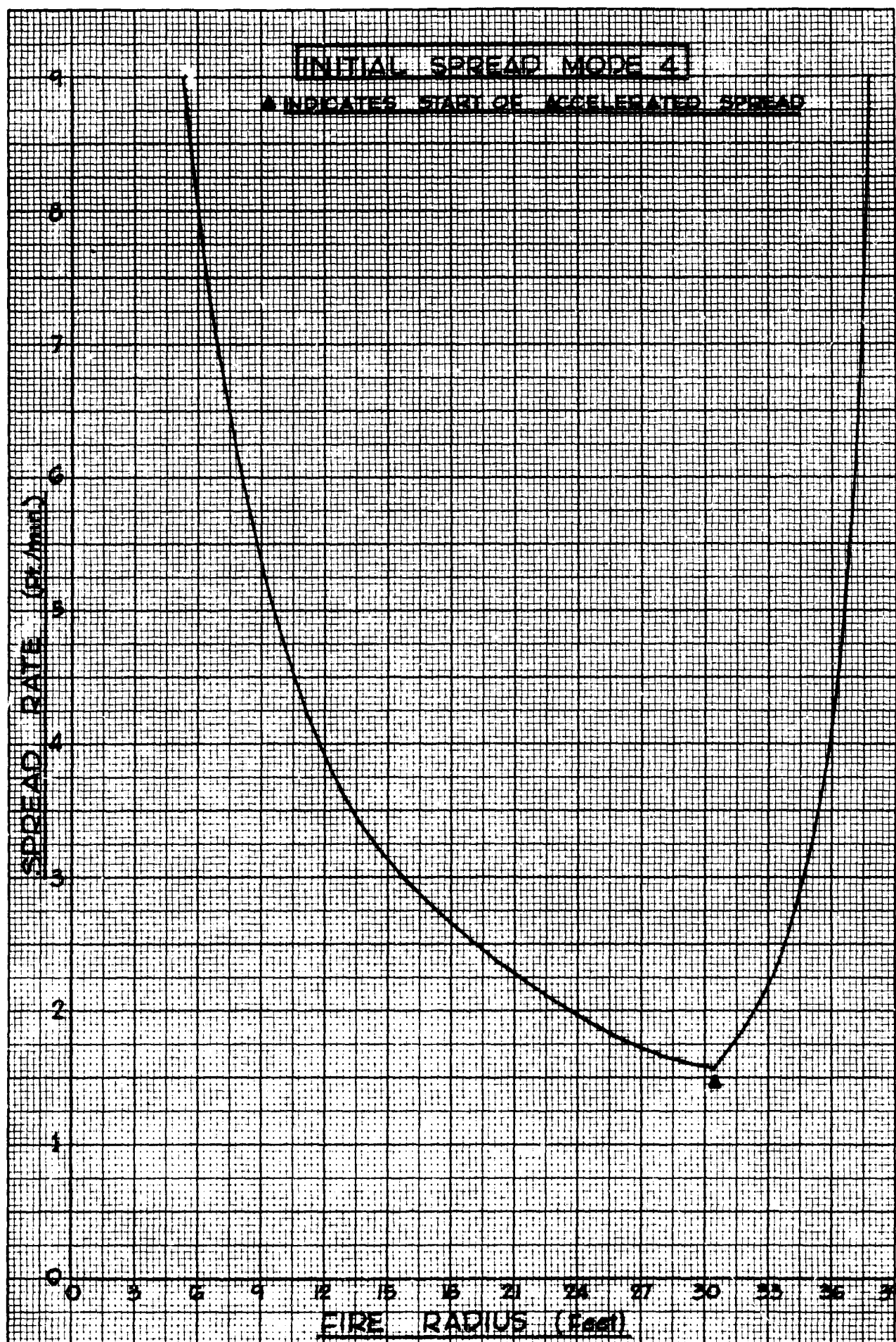


Fig. VIII-8